Australia's National
Science Agency

# Australia's carbon sequestration potential

A stocktake and analysis of sequestration technologies

November 2022

Client name: Climate Change Authority
Client contact: Ben Holt

Lead Authors:

Peter Fitch, Michael Battaglia, Andrew Lenton,

Contributing Authors:

Paul Feron, Lei Gao,Yuan Mei, Allison Hortle, Lynne MacDonald, Mark Pearce, Sandra Occhipinti, Stephen Roxburgh, Andy Steven

Citation: Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A, Australia's sequestration potential, CSIRO.

# Contents

# Figures

# Tables

# Acknowledgments

This project was funded by the Climate Change Authority and the Clean Energy Regulator.

The authors would like to thank and acknowledge the helpful advice provided by Ben Holt, Will Howard, Erik Olbrei and Ramone Bissett.

The authors would also like to acknowledge the contributions of the project technical working group Nicholas Horan, Aleks Kalinowski, Kara Peach, Jocelyn Taylor, Willy Kornoff, Maria, Galatsanos, Ximena Elliot, Penny Reyenga, Alex Brown, Mark Stratton, Haakon Marold, Kanika Singh, Dan Rosauer, Konrad Muller, Max Collett and Paul Ryan.

Short text summaries were produced by Sonja Chandler.

# Executive summary

This report covers the potential for net emissions reductions, through avoided and negative emissions, their costs and risks, and novel technologies that may have the potential to deliver enhanced net emission reductions over the next 5-10 years. It is not designed to be exhaustive, instead it responds to a scope provided by the client to cover a range of negative emissions and avoided emissions technologies.

It draws together existing knowledge from literature and consultation with subject matter experts and synthesises these into key findings. No new modelling or analysis work has been carried out, instead this report represents a state-of-the-art summary. Each technology, where possible, was assessed against a set of core-common criteria including technology readiness, scalability, co-benefits, cost, and sequestration length of storage.

It is important to note that the estimates provided were developed independent of each other and do not consider competition for resources such as energy, water, or land use. Nor have any feedbacks that may occur between the technologies that may affect their scaling (such as feedback from land price) been considered. Consequently, the estimates cannot be added to give a national technical sequestration estimate.

## Technical, Economic and Realisable sequestration.

Throughout this report, the terms technical and economic potential sequestration are used, with sequestration being defined consistent with IPCC[1] definition as the storage of carbon in a carbon pool. The following figure and description should be used to ensure clarity when using the terms.

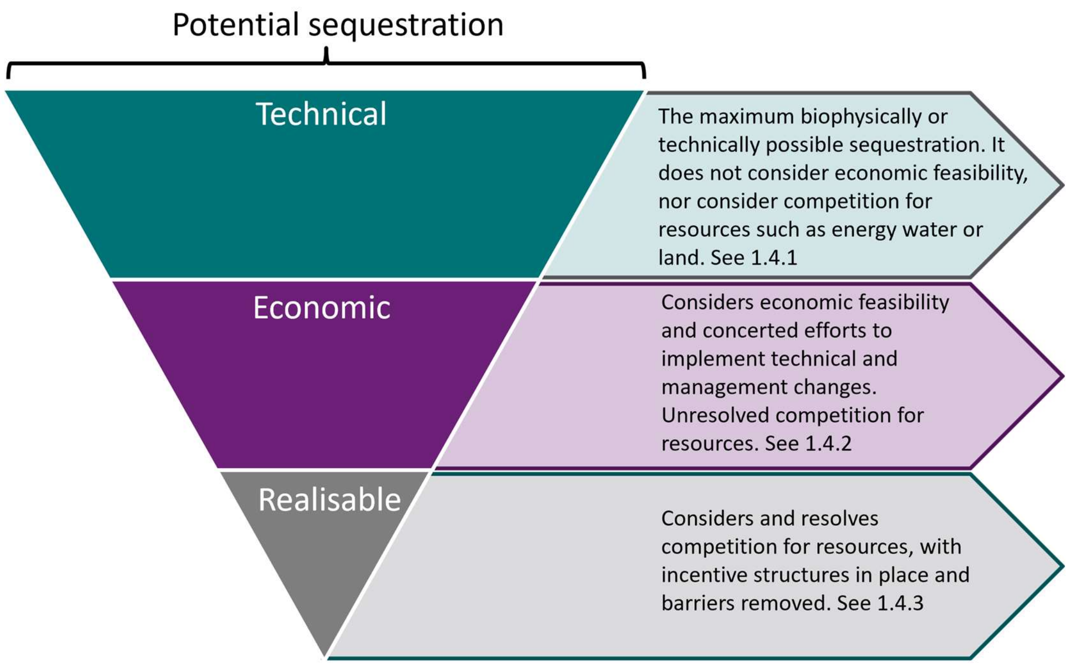



**Figure 1: Technical, Economic and Realisable potential sequestration.**

Figure 1 above illustrates the different potential sequestration types considered in this report.

[1] https://www.ipcc.ch/report/sr15/glossary/

Technical sequestration potential is the maximum technically or biophysically possible sequestration within the definition of the technical option (technology) reviewed. At the most general level, the total potential is defined as future sequestration limited only by current climatic and other biophysical capacity or system storage capacity at the current level of technology. It does not consider socio-economic feasibility nor competition for shared resources such as land, water, or energy.

Economic potential sequestration is the quantity of sequestration attainable given concerted efforts to implement the necessary technical and management steps. Economic sequestration needs to be considered within the context of institutional settings that define the sequestration possibilities. For more discussion on how the report authors have approached this, see section 1.4. In calculating economic sequestration potential, technologies are considered in isolation, and therefore estimates do not consider resource competition. For this reason, and importantly, the estimates are not additive and cannot be summed to form an overall total of national sequestration potential.

Economic sequestration potential could increase with investment in technical innovation and should that innovation succeed, more technical sequestration potential will be realised.

Realisable sequestration potential is sequestration that considers the limitations of resource constraints and implementation feedbacks that can limit scaling. It also considers institutional settings, incentivisation and removal of barriers. This report does not consider realisable sequestration potential, which is anticipated to be considerably lower than the economic sequestration. An approach to uncovering this level of sequestration is provided in chapter 3, Roadmap for a national capability.

Actual sequestration estimates are figures of current sequestration for the period of 2021-22 unless otherwise noted.

## Economic sequestration potential estimates

The figure below is a bubble chart presenting the estimates for economic sequestration for the technologies reviewed in Mt per year $CO_2$-e. The economic sequestration potential estimates in Figure 3, show the commercial readiness level against cost per tonne of sequestration. Bubble size signifies the quantity of sequestration for each technology in Mt per year.

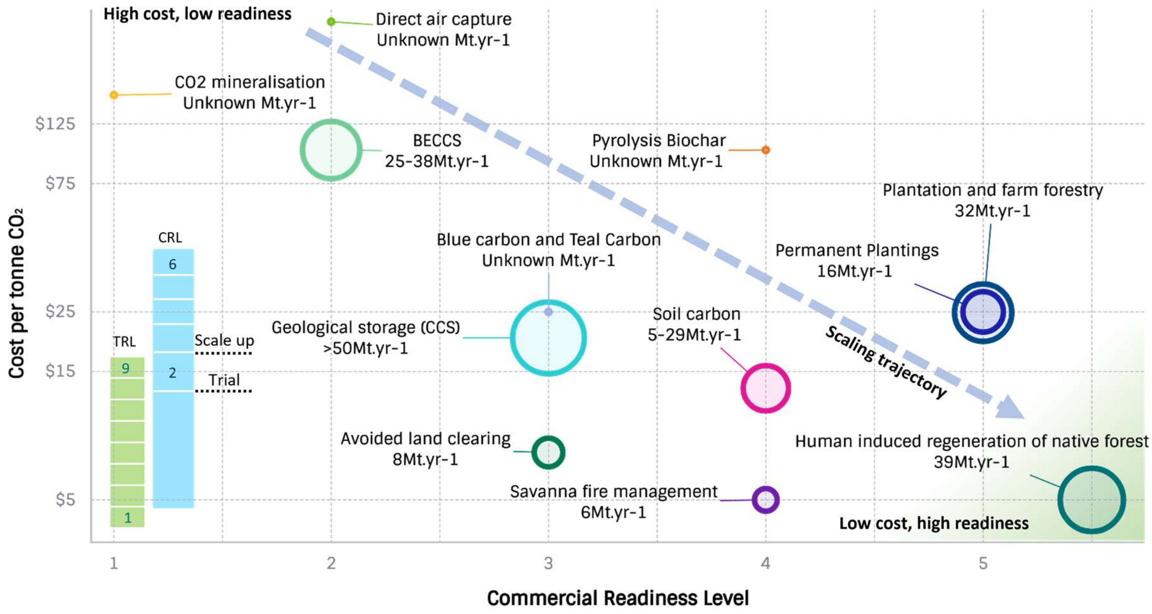



**Figure 3: Economic sequestration for reviewed technologies, indicating their commercial readiness level and cost per tonne. Note the anticipated scaling trajectory to the lower left corner, corresponding to low cost and high commercial readiness.**

Geological storage has greatest technical potential for sequestration with 227 Gt total. It was estimated that if all geological storage projects in development are totalled, an estimate for 2035 economic sequestration would be ~24Mt per year, with an estimate of 50Mt per year for 2050. The economic sequestration for geological storage would increase significantly if BECCS and/or DACs projects are economically viable by this time, adding at least an estimated 28-35 Mt per year for a total of ~55 Mt per year. For reference, the Gorgon Project, Australia's first CCUS project to date, has stored 6.6 Mt of $CO_2$ since becoming operational in August 2019, although this has not been without difficulties (see chapter 12).

Many nature-based solutions have good technical potential for sequestration, particularly permanent plantings, plantation and farm forestry, and soil carbon, with technical potential sequestration of 480Mt per year, 631Mt per year and 115 Mt per year, respectively, by 2050.

The nature-based technologies of plantation and farm forestry and permanent plantings have significant differences between technical and economic sequestration. This difference is related to a combination of factors, some regulatory, but some based on the economics of plantings in remote areas with low sequestration rates. Some fraction of this gap might be closed by removing constraints to planting, incentivising plantings or through innovations that reduce costs of establishment and project delivery considerably

Uptake has been high in nature-based technologies due to their high technology readiness levels and policy support through the carbon farming initiative and the Emissions Reduction Fund (ERF). The ERF[2] fund has

[2]The Australian Government has commissioned an independent expert panel to review the integrity of Australian Carbon Credit Units (ACCUs) under the ERF. The Review will consider whether particular methods subject to recent claims – including the human-induced regeneration method – continue to comply with the scheme's integrity standards. This report does not pre-judge the outcomes of the Chubb review.

acted to accelerate the Commercial Readiness Level (CRL) of these technologies and driven by the high potential and the supportive policy position, significant investment into these technologies (especially soil carbon) has flowed.

## Technical, Economic and Realisable sequestration difference

The difference between actual sequestration and economic potential sequestration (where known) is significant. However, this difference should be viewed with some caution, given the key unresolved gap, reflected in the real opportunity, is the difference between the actual and the realisable sequestration. Realisable sequestration will be lower than economic sequestration, with the difference in part due to resource competition. For example, competition for the same land base affects realisable sequestration for plantation and farm forestry.

## Sequestration Costs

There is a strong relationship between cost per tonne of sequestration and commercial readiness level. Where costs are high, projects are yet to be developed. Biochar, BECCS and Direct Air Carbon Capture and Storage have significant sequestration potential but have high costs. These are areas where investment into research to bring down the unit cost associated with capture could increase national sequestration potential.

If early-stage projects (such as biochar or BECCS projects) could be aligned to other areas of co-benefit, such as supporting afforestation in areas in need of hydrological rebalance, or producing products that could be embedded in downstream industries (such as biochar into plastics), then co-funding opportunities could result.

The anomaly is geological sequestration, with low unit sequestration costs and low CRL. This finding suggests the barriers are different: high initial capital costs, implementation difficulties and regulatory barriers. Approaches to unlocking the potential of this opportunity are different and involve de-risking investment (underpinning knowledge infrastructure that shows where prospective sinks might be etc.) and potentially concessional loans or forward contracts on sequestration to offset the high initial investment.

## Estimates for 2035

It was not possible at this stage to provide 2035 estimates for many of the technologies as the necessary modelling has yet to be done, and rates of technology uptake will depend strongly on the carbon price. In some ways, it is easier to forecast estimates for 2050 rather than 2035, where it may be assumed that demand will be high, and projects may scale towards their realisable levels.

Note also that it was not possible to produce economic sequestration estimates for mineral carbonation, DAC, Blue carbon and pyrolysis biochar, given the emerging nature of these technologies and low Commercial readiness Levels (CRLs).

## Summary of technologies

The infographics below present the emission type, quantity, cost, length of storage and resource competition for the reviewed technologies. The legend for the infographic is in Figure 5 below. For more comprehensive information on the findings, see Key Findings in chapter 2.

| | Permanent plantings | Plantation and Farm Forestry | Human induced Regeneration of native forest | Avoided clearing | Savanna fire management | Soil Carbon |
|---|---|---|---|---|---|---|
| Emission Type | Negative | Negative | Negative | Avoided | Avoided or negative | Avoided or Negative |
| Capture Technology | | | | | | |
| Storage Technology | | | | | | |
| Cost per tonne | $$ | $$ | $ | $ | $ | $$ |
| Length of storage | | | | | | |
| Resource competition | | | | | | |
| 2021-22 Actual Sequestration | ~0.5[1]<br>2.1[2] Mt.yr-1 | ~0.1[1]<br>11.5[3] | 6.4[1]<br>20[2] | 2.3[1] | 1.46[1]<br>5.6[4] | 0 Mt.yr-1 |
| 2050 Economic Potential | ~16 Mt.yr-1 | 32 Mt.yr-1 | 39 Mt.yr-1 | 7.7 Mt.yr-1 | 6 Mt.yr-1 | 5-29 Mt.yr-1 |

| | Blue carbon (coastal) | Biochar | CCS | BECCS | DAC | Mineral Carbonation |
|---|---|---|---|---|---|---|
| Emission Type | Avoided or Negative | Negative | Avoided or Negative | Negative | Enabling technology | Negative |
| Capture Technology | | | | | | |
| Storage Technology | | | | | | |
| Cost per tonne | $$ | $$$$ | $$-$$$ | $ | $$$$$ | $$$-$$$$$ |
| Length of storage | | | | | | |
| Resource competition | | | | | | |
| 2021-22 Actual Sequestration | 1.1[6] Mt.yr-1 | 0.04 Mt.yr-1 | 2.26 Mt.yr-1<br>(2020-21) | No Estimate | No Estimate | 0.1 Mt.yr-1 |
| 2050 Economic Potential | No Estimate | No Estimate | >50Mt.yr-1 | 25-38Mt.yr-1 | No Estimate | No Estimate |

**Figure 4: Summary diagrams for technology summary. :Where there is insufficient data or evidence for inclusion no estimate is provided. [1] ACCUS' issued 2021-2022 extracted from the ERF project register July 2022. [2]AEGIS 2010-2020 includes soil carbon as well as living biomass and forest debris. [3] AEGIS 2010-2020 includes soil carbon as well as living biomass and forest debris but excludes harvested wood products.[4]AEGIS 2016-2020 includes biomass, debris and soil carbon. [5]Both Bioenergy and direct air capture use geological storage for sequestration. [6]AEGIS 2010-2020 includes soil carbon as well as living biomass and debris.**

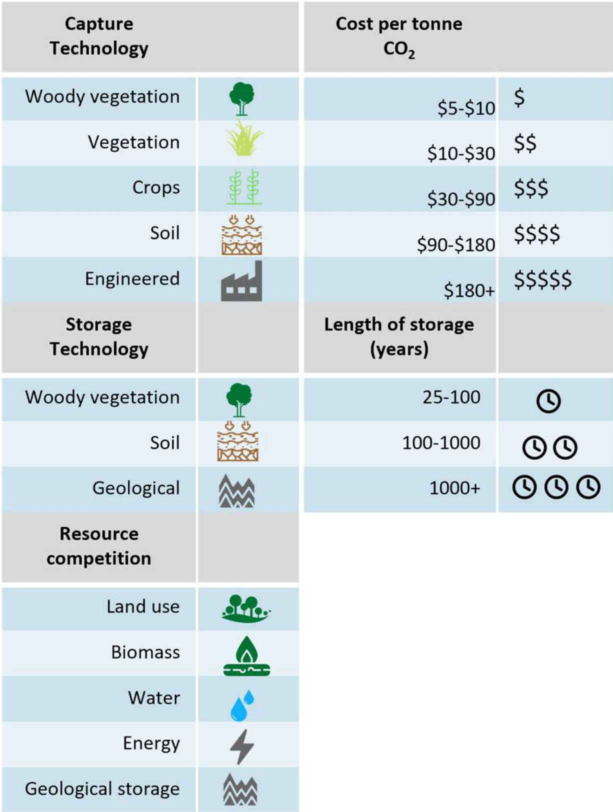



**Figure 5: Legend for the summary of technology diagrams.**

## Technology Scaling considerations

There are co-benefits associated with many of the reviewed technologies, which can be leveraged to assist uptake and scaling. Examples of co-benefits include socio-economic benefits that flow back into local communities, and environmental benefits such as improved soil health and/or biodiversity benefits.

If early-stage projects (such as biochar or BECCS projects) can be aligned to other areas of co-benefit, such as supporting afforestation in areas in need of hydrological rebalance or producing products that could be embedded in downstream industries (such as biochar into plastics), then co-funding opportunities are created.

Another technology enabler is the creation of market mechanisms that encourage benefit stacking (where multiple payments can be paid for the same activity delivering a range of benefits) to improve the overall value proposition of technology implementation.

For most of the technologies reviewed, further assessment of the benefits, co-benefits and costs and a better understanding of land use and resource trade-offs could support scaling.

Some technologies require proximity to concentrated feedstocks (BECCS, Biochar) or proximity to those who will use products (biochar, $CO_2$ captured by DAC for mineral carbonation or geological storage) if they are to be economically scaled. Coordination between industry and government can assist in scaling such industries.

As many of the opportunities for sequestration are in regional areas, regional benefits of the technologies are critical to achieving social license to operate, uptake and the scaling required to realise the transition potential into economic sequestration. Further, regional opportunities will require low-cost supply chains and logistics to enable and support these sequestration activities.

Cost per unit of sequestration remains a barrier for some technologies. This issue is discussed in more detail in the technology review chapters. It can be overcome by investment in research, development, and extension (extension in the broadest sense of commercial trialling and business model development) for those technologies that have the best opportunity to contribute to our national goals.

In a few cases, regulatory barriers present a hurdle. Some examples of this are the complex permitting for geological storage and the complexities of land ownership with blue carbon.

Measurement and verification requirements present variable challenges to scaling the technologies and supporting robust market uptake. Improved ability for measurement standards to confirm the robustness of the sequestration is required for some technologies and needs to be developed consistently with international developments.

## Resource competition

The infographics above display possible resource competition for each technology. All the nature-based technologies, in some way, will be competing for land and water use to varying degrees. Figure 6 depicts the shared storage medium for biological technologies - above-ground biomass and soil, and similarly the competition between BECCS and CCS for geological storage. BECCS and biochar are competing for biomass. CCS, DAC and mineral carbonation are competing for energy and water.

Emerging demands for biomass feedstocks in other areas of avoided emissions and the bioeconomy, such as the use of charcoal as an alternative to coal in smelting processes, the use of biomass for future plastics industries and the rise of a biogenic sustainable aviation fuel will impact on the economics of scaling these technologies. As discussed above and in more detail in chapter 1.4, the technologies have been reviewed independently and don't consider resource competition. Each of the technologies requires resources to provide sequestration and in some cases to be combined. How the resources are distributed ultimately between competing demands to achieve highest and best use is a question that remains outstanding. The next steps section below presents a plan for developing a capability to resolve that competition.

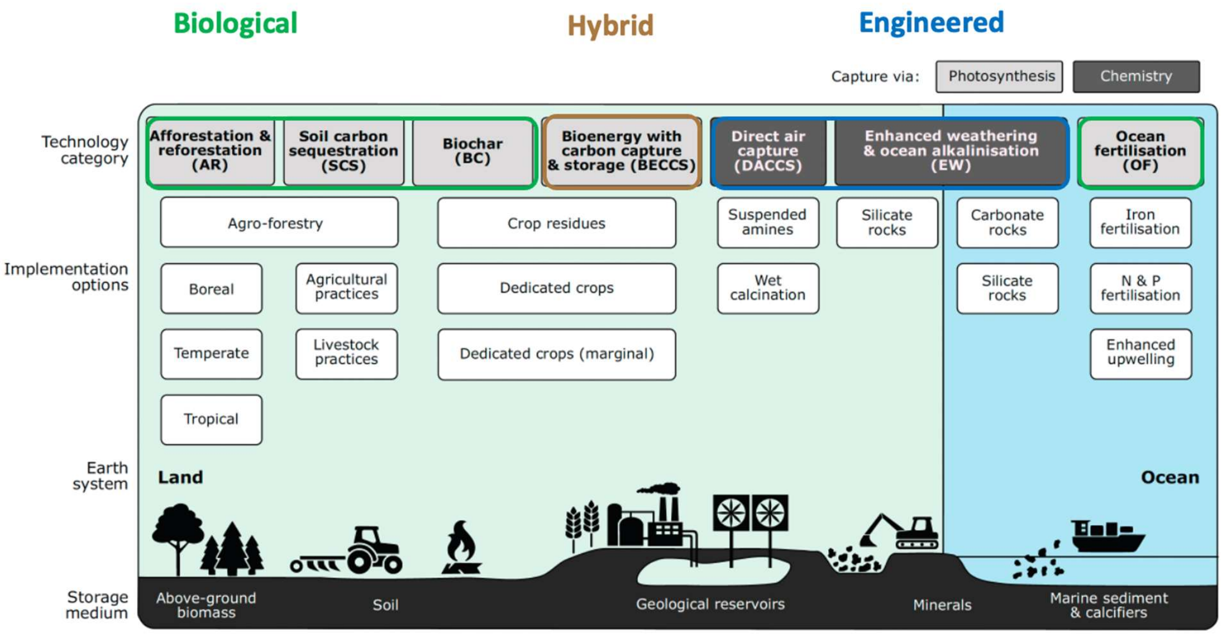


Figure 6: Topology of different technologies adapted from Minx et al (2018).

## Australia's Opportunity

Australia has good opportunities to sequester carbon via a range of technologies. Each of those technologies alone is not sufficient to provide a pathway to Australia's emissions reduction target. Rather a portfolio approach combining the best set of technologies will be required. A means to identify the best value portfolios of options based on Australia's competitive advantage is discussed in the next section and chapter 3. Development of all sequestration portfolios need to consider that nature-based solutions will saturate – storage will increase and eventually slow and stop as forests grow to maturity or soils reach their new equilibrium soil carbon values.

Australia is well positioned with abundant land-resources, significant geological storage capacity, vast marine estate and low-emission-energy resource potential (CSIRO Low Emission technology Roadmap) to translate the potential identified in this report into realisable sequestration.

There are many potential pathways for the use of $CO_2$ once captured either from Direct Air Capture of point sources of $CO_2$. These pathways include $CO_2$ use in many high-value long-lived products (e.g. cement), which ultimately present opportunities and options for Australia. These pathways are well covered in the CSIRO $CO_2$ utilisation roadmap and not covered in this report.

In addition, Australia has a well-developed carbon market which is a necessary institutional structure to support the scaling of these technologies. Further, Australia has good underpinning knowledge infrastructure (such as the national soil grid and downscaled meteorological data and modelling frameworks such as FULLCAM).

Australia also possesses a highly skilled and digitally enabled workforce to take advantage of advanced methods to target opportunities to the most prospective areas. Other workforce skills include conducting sound risk analyses to de-risk investments and finding new, cheaper, and more robust ways to monitor, report and verify carbon sequestration projects.

## Next Steps – the Roadmap for a national capability

In this report, the current state of a range of sequestration options has been produced. This has generated a series of potential and economic sequestration estimates for 2050. However, the rate and advances in technology development and uptake trajectory in that period are unclear, though we know they are changing rapidly. Estimates made today may be rapidly outdated.

A new national capability is required to provide improved estimates, identify, and assess best value portfolios of options, and guide investment and the design of incentives that unlock emerging opportunities.

This national capability would support the identification of portfolios of negative emissions technologies as part of Australia's Nationally Determined Contributions. This requires an integrated modelling assessment (IAM) approach informed by innovations in emerging technologies. An IAM approach that coupled economic, energy system, and earth system/land use models would allow exploration and quantification of national and regional trade-offs and feedbacks of different portfolios of negative emissions technologies and quantifying their efficacy.

The IAM system could also assess benefits, co-benefits, and risks over time. The IAM approach will provide the capacity to develop optimised negative emissions portfolios that account for different emissions trajectories and pathways. For example, what is the balance of emissions reduction compared with offsetting we are planning? It will allow assessment of alignment with other policy settings around regional economies, industry sector transitions, environmental impacts, co-benefits and risk appetites. Importantly, it would enable recurrent estimation and revision considering technology improvements or regulatory changes.

Traditionally studies and reports that have explored this transition have focused on the economic pathways and largely ignored the regional impacts of climate change and variability on negative emissions technologies

The path to developing and implementing this national capacity will require establishing a steering group responsible for this development made up of representatives from industry, government, universities, and research agencies.

The development of national capability will require significant investment and is likely to be of the order of $3-5M over 18-24 months.

# Introduction

## 1 Report Introduction

Permanently removing significant amounts of carbon dioxide from the atmosphere combined with ambitious emissions reductions, provides the only realistic path for the world to reach the goals of the Paris Agreement (IPCC AR6 Report (2022); Figure 1.1). It is estimated that globally up to 10 Gigatonnes of $CO_2$ per year will need to be permanently removed from the atmosphere annually by 2050, with up to 20 Gigatonnes of $CO_2$ per year needed to maintain net zero by 2100 (NASEM, 2019). This report is a review of the status of a number of avoided and negative emissions technologies, in support of reaching Australia's and the world's climate goals.

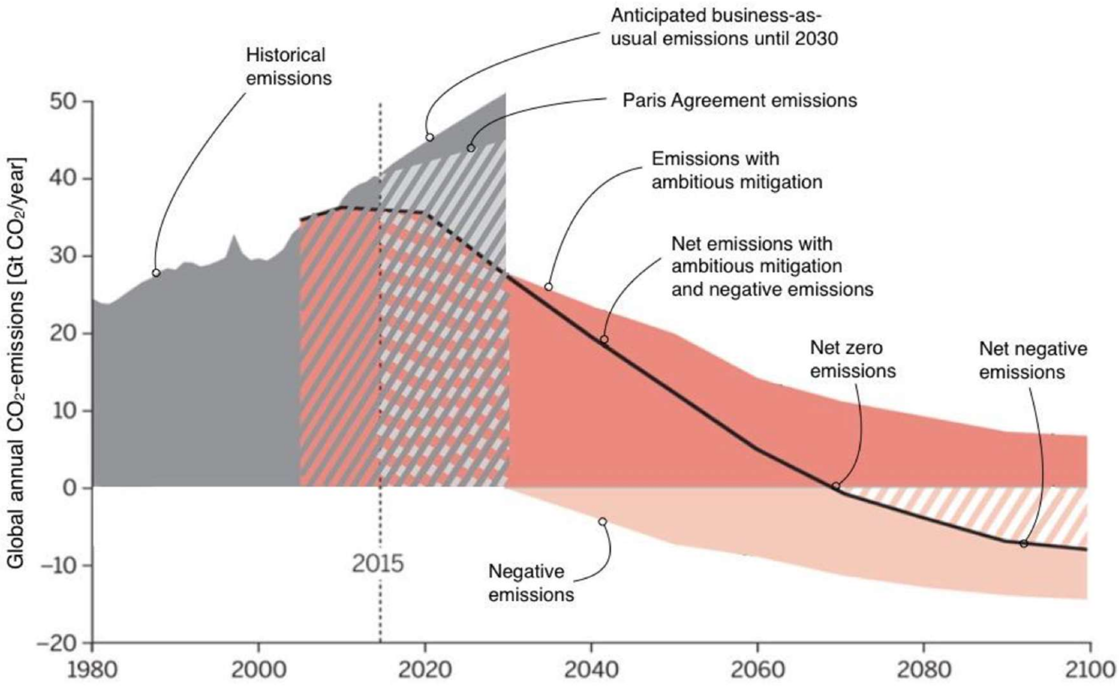



**Figure 1-1: The pathways to reaching the goals of the Paris Agreement[3] require both ambitious emissions reduction (mitigation) and negative emissions (Honegger et al, 2017, adapted from Anderson and Peters, 2016)**

### 1.1 Report Scope

This report covers the potential for use of negative emissions and storage approaches (avoid emissions) to assist in achieving and maintaining net zero emissions. The report examines their costs and risks, and emerging technologies with the potential for greenhouse gas removal and sequestration in the periods to

[3] United Nations Framework on Climate Change (UNFCCC): Adoption of the Paris Agreement, 21st Conference of the Parties, https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

2050. The report is not exhaustive but rather responds to the scope of approaches provided by the client; covering a number of negative emissions and avoided emissions technologies.

It draws together existing knowledge and synthesises these into key findings, both from literature and consultation with subject matter experts. No new modelling or analysis work has been carried out: it is a state-of-the-art summary. Each technology, where possible, is assessed against a set of core-common criteria including technology readiness, scalability, co-benefits, cost, and length of storage.

This report also seeks to identify key risks and potential system impacts of the different approaches to inform investment in work to identify and mitigate impacts through regulation, application practice or technology refinement.

## 1.2 Negative Emissions

Negative Emissions results from the removal and sequester carbon dioxide ($CO_2$) and other non-$CO_2$ Greenhouse Gases (e.g,. Methane and Nitrous Oxide) from the atmosphere with the intent of reducing the atmospheric greenhouse gas (GHG) concentrations. Negative Emissions usually refer to all (GHGs), encompassing $CO_2$ and non- $CO_2$ greenhouse gases, while CDR often refers to carbon dioxide alone. In this report, we refer to negative emissions, which encompasses the broadest definition of GHG removal. Importantly, negative emissions refer to the deliberate removal of GHGs from the atmosphere.

The imperative and case for negative emissions is very strong; it has become widely accepted that it cannot serve as a substitute for deep emissions reductions but that it can fulfil multiple complementary roles; these include (IPCC, 2022):

1. further reduce net GHG emission levels in the near term,
2. counterbalance residual emissions from ‘hard-to-transition’ sectors, such as $CO_2$ from industrial activities and long-distance transport (e.g., aviation, shipping), or non-$CO_2$ GHGs from agriculture, to help reach net zero emissions in the mid-term,
3. achieve and sustain net negative emissions in the long-term, by deploying Negative Emissions at levels exceeding annual residual gross GHG emissions.

The underlying principle of negative emissions is the acceleration or enhancement of natural carbon cycle processes, to enhance the removal of $CO_2$ from the atmosphere, and sequester this $CO_2$ on land, in the ocean, or in geological reservoirs.

Negative emissions are delivered via one of more enabling technologies which can capture <u>and</u> store GHGs, away from the atmosphere, often termed Negative Emissions Technologies (NETs). NETs remove $CO_2$ and, in some cases non-$CO_2$ GHG from the atmosphere via biological (photosynthetic) or chemical pathways. Some NETs are well understood and are actively being implemented. Many are immature or emerging and will require research, development, and demonstration (RD&D) to bring them to a level of readiness (technology readiness level or ‘TRL’) and commercial readiness level (CRL) for scaling. Negative Emissions Technologies (NETS) also only refers to technologies that are net negative as the result of an end-to-end system in which the processes sum be net negative.

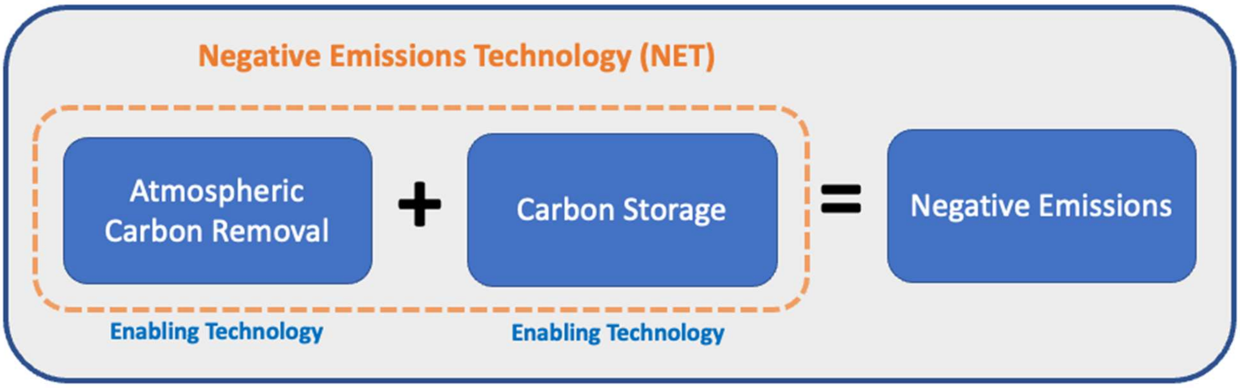



Figure 1-2: The elements of Negative Emissions Technologies (NETs)

The elements of a Negative Emissions Technology are seen above in Figure 1-2, and are considered as a composition of enabling 'capture' and 'storage' technologies. As stated above, systems that are net negative across the whole supply chain are termed NETs.

## 1.3 Avoided Emissions

Avoided emissions refer to deliberate activities that prevent GHGs from being released into the atmosphere. Avoided emissions, sometimes termed Carbon Avoidance, are part of a portfolio of mitigation approaches encompass activities from active land management to point source capture and storage from industrial process streams (Figure 1-3).

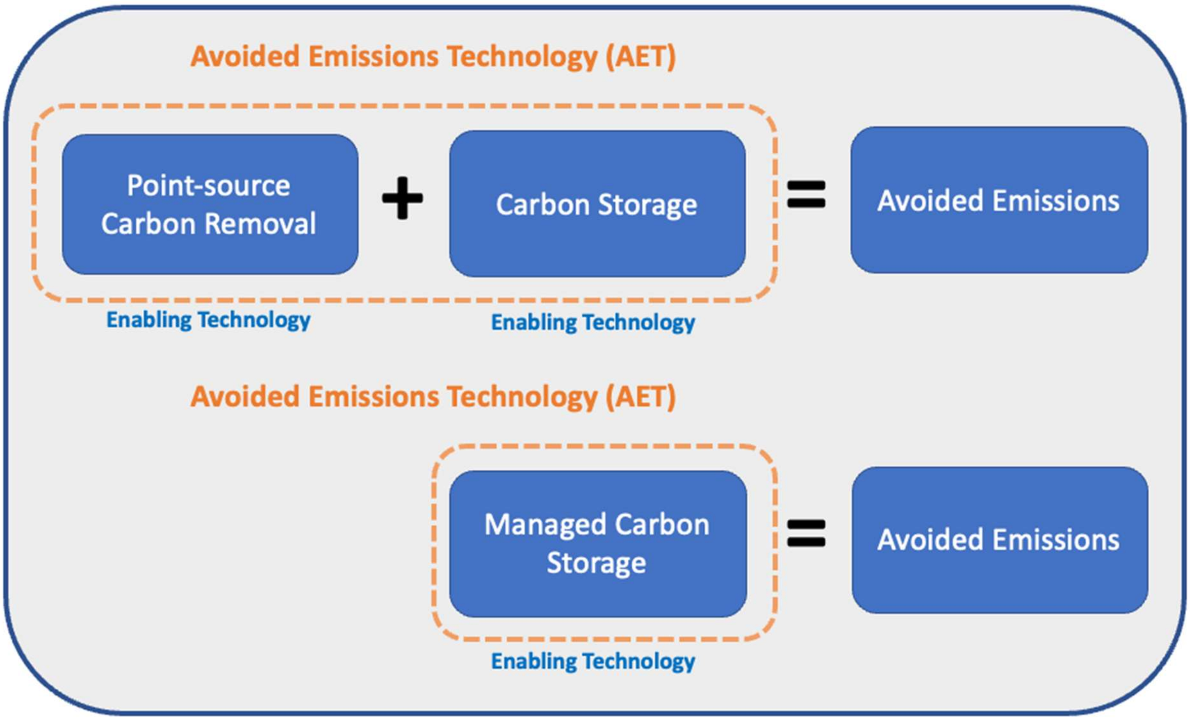



Figure 1-3: The elements of Avoided Emissions Technologies (AETs)

### 1.2.1 The Australian Context

In line with global agreements to reach net zero emissions, Australia recently committed to a revised emissions reduction of 43% below 2005 levels by 2030 and net zero by 2050 (Australia's UNFCCC NDC update 2022). This will require significant additional sequestration capacity to reach these targets. By way of comparison total Australian Carbon Credit Unit (ACCU) delivery was 12.39M ACCUs with 13.9M ACCUs scheduled for 2022 (CER quarterly carbon market report March 2022).

### 1.2.2 Deployment of AETS and NETs

Many AETs and NETs, including approaches that deliberately enhance natural sinks of atmospheric $CO_2$, are particularly vulnerable to climate variability and change (e.g., drought and fire). In addition, their deployment at the anticipated scales requires large-scale human engineering, competition for often scarce resources and the potential direct and indirect manipulation of ecosystems at unprecedented scales, which have the potential to impact system function and resilience, and, ultimately, the ecosystem services they provide. Even in the case of engineered and. More mature technologies, these impacts and anticipated feedbacks remain poorly understood and quantified and need to be considered as part of ongoing research and assessment.

This report seeks to identify some of the key risks and benefits from a set of prospective AETs and NETs and identifies actions that can accelerate the development of these technologies and the co-benefits and risks associated with their widespread uptake. A related matter is that AETs and NETs need to be embedded into systems of use to be scalable, which accounts for both the technological and commercial readiness of the technology. Systems of use are the broader set of enabling regulations, infrastructure, capability, value chain connections and market mechanisms that allow technology to create value and be widely adopted. For example, soil carbon farming could remove a significant quantity of atmospheric GHG and deliver co-benefits to farmers in terms of drought resilience and nutrient retention. Many marginal sequestration cost curves (MACCs) have suggested that these co-benefits are cost-effective at low or even negative marginal sequestration costs. However, early regulatory framings with high measurement and compliance costs failed to unlock this potential. Unlocking the potential requires adjacent technological inventions to reduce measurement costs and parallel regulatory reform to allow for these new and lower-cost assessment techniques (which has occurred in later ERF methods). AETs and NETs are required to deliver national and global goals: these are delivered by systems of use, not enabling technologies in isolation. To this end, this report, where possible, looks at barriers to adopting different technologies

### 1.2.3 The need for a portfolio of approaches

All net emissions reduction approaches (AETs and NETs) rely on the availability of different inputs such as land, water, energy, and the capacity of a suitable carbon storage medium. For example, land and water availability is a limiting factor for technologies that rely on purposely grown biomass, like bioenergy with carbon capture and storage (BECCS) or biochar from the first-generation feedstock. The amount of land and water available to grow biomass puts an upper ceiling on carbon removal based on photosynthesis. It is essential to understand these limiting factors so we can appropriately prioritise RD&D investment in technologies based on their annual carbon removal potential and ultimate quantum of economic carbon sequestration. Biophysical limits will ultimately determine whether a CDR can be implemented at a sufficient scale to make a meaningful difference to atmospheric GHG concentrations. While we need to avoid ‘picking winners’, we need to understand these factors to ensure we are investing in technologies likely to have the most significant impact. This report looks to determine the technical and economic scale of technologies to guide this investment.

The scale of carbon sequestration required for our national and global targets looks challenging when considering the biophysical limiting factors of any one technology, such as the BECCS (Anderson and Peters, 2016). But different technologies have different operating mechanisms and rely on different natural resources. Understanding the theoretical limits to the emissions reduction associated with each approach allows us to strategically plan a combination of technologies to meet our sequestration needs. A broad portfolio of net emissions reduction that utilises different AETs and NETs, each with its own set of inputs, and desired co-benefits relevant at the regional scale, will more likely deliver a more resilient and sustainable portfolio of net emission reductions.

### 1.2.4 The need for a national foresighting capability

To ensure AETs and NETs are available and ready to be scaled for deployment in the time frames needed, we must foresight the key success factors for scaled implementation and incorporate these factors into an accelerated RD&D process. By foresighting, we mean developing an understanding of the factors that typically are barriers or enablers to the scaled diffusion of innovation and addressing those factors during early research. The ability to carefully design for these factors will determine that rate at which technologies, both AETs and NETs can be successfully scaled and the extent to which their scaling maximises opportunities for co-benefit delivery and minimises competition and can impact social licence. We include in this need the requirement to understand how scaling of any technology creates competition with other technologies and with exogenous system factors such as land and input prices (so for example if we deploy many technologies that utilise land how does this influence land prices for food production). In this report, we outline a roadmap for foresighting the future supply of AETs and NETs with ability to understand the influence of technology development, economic system factors and policy levers on the spatio-temporal delivery of offset supply.

## 1.3 Typology of Technologies

There are three approaches considered here (figure 1-3), following Minx et al (2018):

**Biological:** These refer to approaches that take advantage of natural biological systems to take up and sequester atmospheric carbon dioxide (NETs) e.g., afforestation/reforestation; or those that prevent existing sequestered carbon from being released into the atmosphere (AETs) e.g., avoided clearing. These can also be referred to as Natural, Nature-Based or Natural-Climate Solutions. Biological approaches are associated with the sequestration of $CO_2$ and non-CO2 GHGs and are often reported in units of $CO_2$-e (or $CO_2$-eq) referring to the sum of $CO_2$ and the $CO_2$ equivalence on non-$CO_2$ greenhouse gases. In this report biological approaches are reported in units of $CO_2$-e.

**Engineered:** These refer to approaches that rely on chemistry to capture and sequester atmospheric carbon dioxide (NETs) e.g., mineral carbonation; or those that capture carbon from point sources for sequestration (AETs) e.g., Carbon Capture and Storage (CCS). In many cases, these solutions involve combining two different capture and storage technologies, such as Direct Air Capture and geological storage. This also includes many $CO_2$ uses in high-value long-lived products such as cement covered in CSIRO's $CO_2$ Utilisation Roadmap (Srinivasan et al, 2022). Engineered approaches in this report are reported in units of $CO_2$.

**Hybrid:** Some approaches that combine biological capture and geological storage. Examples of this include Bioenergy Carbon Capture and Storage (BECCS) which involves using Biomass to capture carbon, produce energy and then capture sequestration of the carbon released and captured within this process into geological stores. In this report hybrid approaches are reported in units of $CO_2$-e as they rely on biological capture.

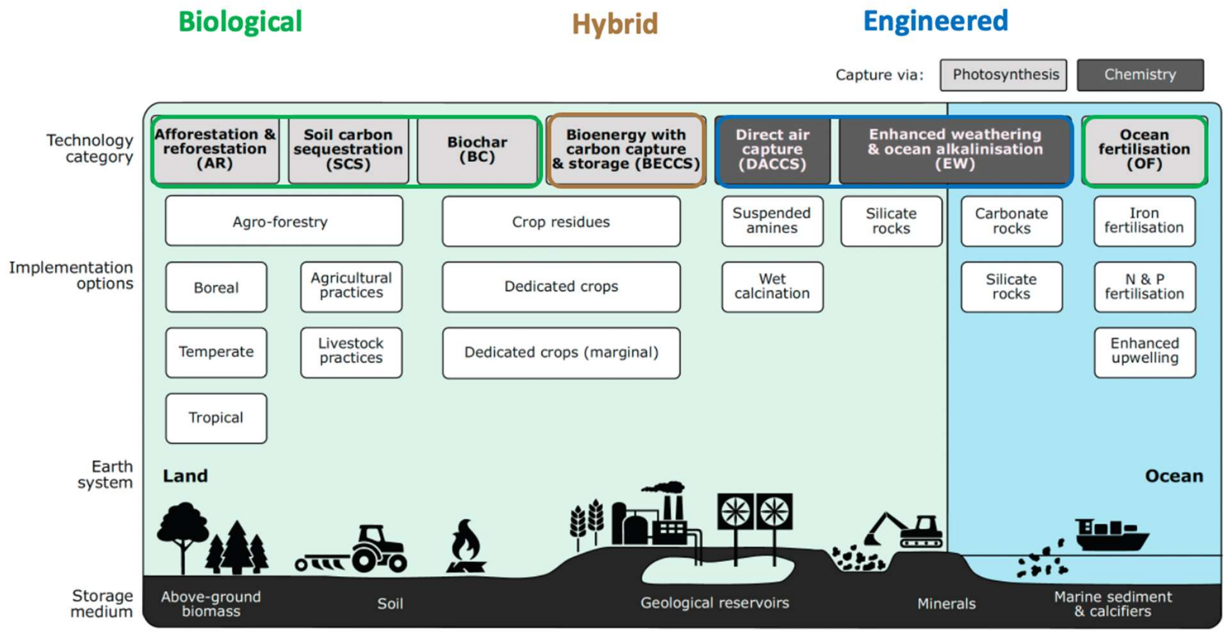



**Figure 1-4: Topology of different technologies adapted from Minx et al (2018)**

## 1.4 Core Criteria

The core criteria used in this report are designed to assess the current state of the technology, the scaling pathway, and risks and barrier to uptake. The goal of having a common set of criteria is to allow an easier integration and synthesis, so that an overall picture of the current and potential future scenario for uptake of negative carbon emissions technologies can be developed.

**Sequestration Potential**

Sequestration Potential, through NETs or AETs falls into three categories:

1. **Technical sequestration:** The maximum biophysically (or technically) possible within the definition of the option (referred to in this report as technical sequestration). At the most general level total potential is defined as future sequestration limited only by current climatic and other biophysical capacity or system storage capacity at the current level of technology efficacy.
2. **Economic sequestration:** Assess the level attainable given concerted efforts to implement technical and management changes (called Attainable in Eady et al. 2009). Economic sequestration needs to be considered within the context of institutional settings that define the sequestration possibilities. For more discussion on how the report authors have approached this, see the approaches below.
3. **Realisable sequestration:** this report does not consider realisable sequestration. In calculating economic sequestration, AETs and NETs are considered in isolation, however, there will be competition for shared resources (e.g., land, water, and energy). between sequestration technologies and several intended and unintended system feedbacks, impacts and co-benefits. This will ultimately restrict their scalability and the role they will play in any portfolio of AETs and NETs, particularly at the regional scale.

This report focuses on the potential and economic sequestration and outlines the Roadmap to translate this economic sequestration into realisable sequestration.

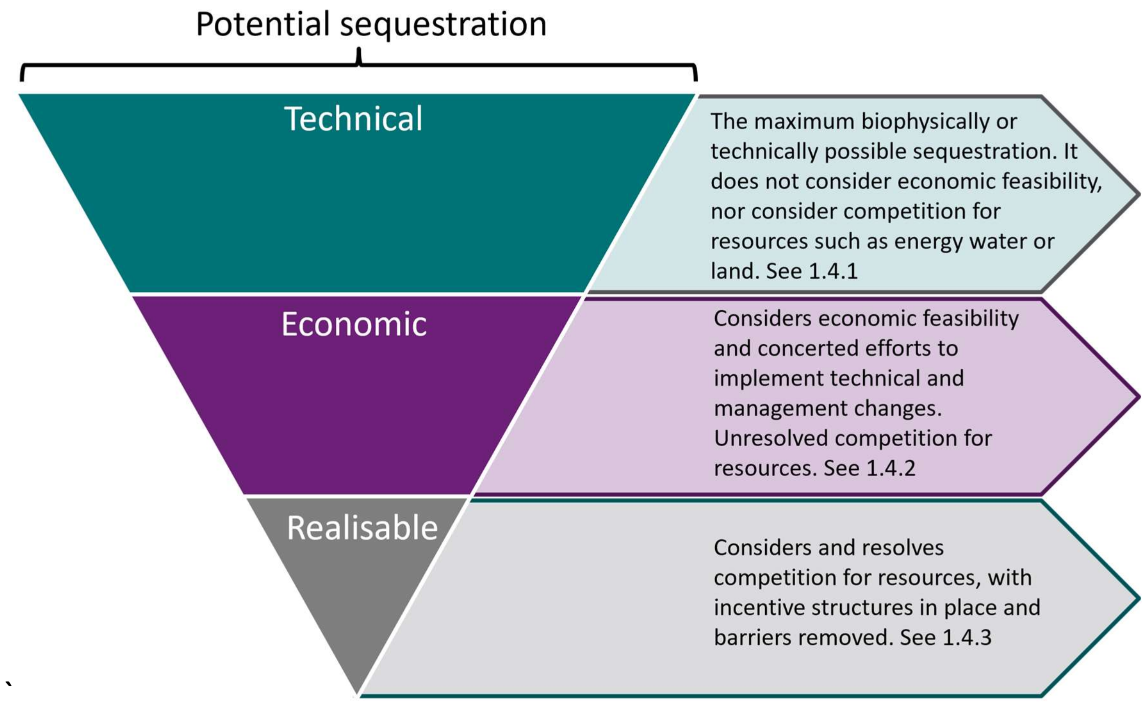



**Figure 1-5: Technical, economic and realisable potential sequestration**

Figure 1-5 above illustrates the different potential sequestration types considered and defined above as used in this report. Sequestration potential is depicted as a funnel, to convey the notion that potential decreases as the economics, incentive structures and resource competion limit the technical sequestration potential.

**Approaches to determining potential and economic sequestration**

In assessing the AETs and NETs, the chapter authors use their expert knowledge to identify and use the best available evidence (reports, scientific literature, exemplars, or case studies) for our best attempt at providing defensible estimates. As well, the project working group has helped alert chapter authors to additional relevant evidence which has been included. In some cases, multiple estimates are provided indicating the variation in evidence, and that there is no agreed single figure for sequestration.

For the vegetation and soil technologies, estimates are provided based on modelling, which estimates sequestration potential for Emission Reduction Fund (ERF) methods. ERF methods have assumptions and constraints and are listed specifically in each of the chapters. These estimates provide a biophysical limit for the technical sequestration and scheme-specific economic sequestration. As this report collates existing knowledge, the modelling study (Roxburgh et al, 2020) is a useful ERF view on sequestration potential. In some cases, it is a lower bound on potential (relaxing some constraints could increase sequestration quantity) and in some case close to the actual potential limit (biophysical limit). Where other evidence is easily accessible that provides other views on potential and economic sequestration estimates such as the National Greenhouse Gas Inventory (NGGI) or State based data such as historical land clearing, they are included. It is important to note that in this report that estimates for technical and economic sequestration do not imply that sequestration is solely reliant on the ERF and could occur via other means of incentive or policy settings.

It was out of scope for this report to evaluate relaxing constraints or to evaluate different policy interventions, rather the focus is to highlight the barriers and scale drivers for each technology.

**Approaches to determining actual sequestration**

Actual sequestration estimates are figures of current sequestration for 2021-22 unless otherwise noted. These estimates are from different sources, including National Greenhouse Gas Inventory and the Emissions Reduction Fund project register.

**Competition for resource availability**

Many of the technologies reviewed in this report have resource demands that rely on shared resources, e.g., geological storage for CCS and BECCS, biomass for bioenergy and permanent plantings etc. Identifying which technologies are ultimately the most desirable will require resolving the trade-off between the social, environmental, and economic uses of shared resources. In this report, we do not consider the trade-off between resources, instead, each technology is considered individually. Consequently, this means the economic potentials of each technology are not additive due to finite resource availability.

**Technology Readiness Potential and Commercial Readiness**

A common approach to understand the scaling options and trajectories for CDR is to assess the technology and commercial readiness. Technology Readiness Levels (TRL) is used commonly for this purpose and provide a common rating for maturity on a range from 1 -9. TRL 1 is the lowest maturity level indicating that technology is at the basic research stage, and 9 the most mature indicating fully developed, and proven and operational technology. The complementary Commercial Readiness Level (CRL) is used to assess the commercial status of the technology. This assessment provides an indication of where the technology is positioned for full scaling and commercial implementation. The TRL/CRL description used in this report is from ARENA and is included in Figure 1-6 below.

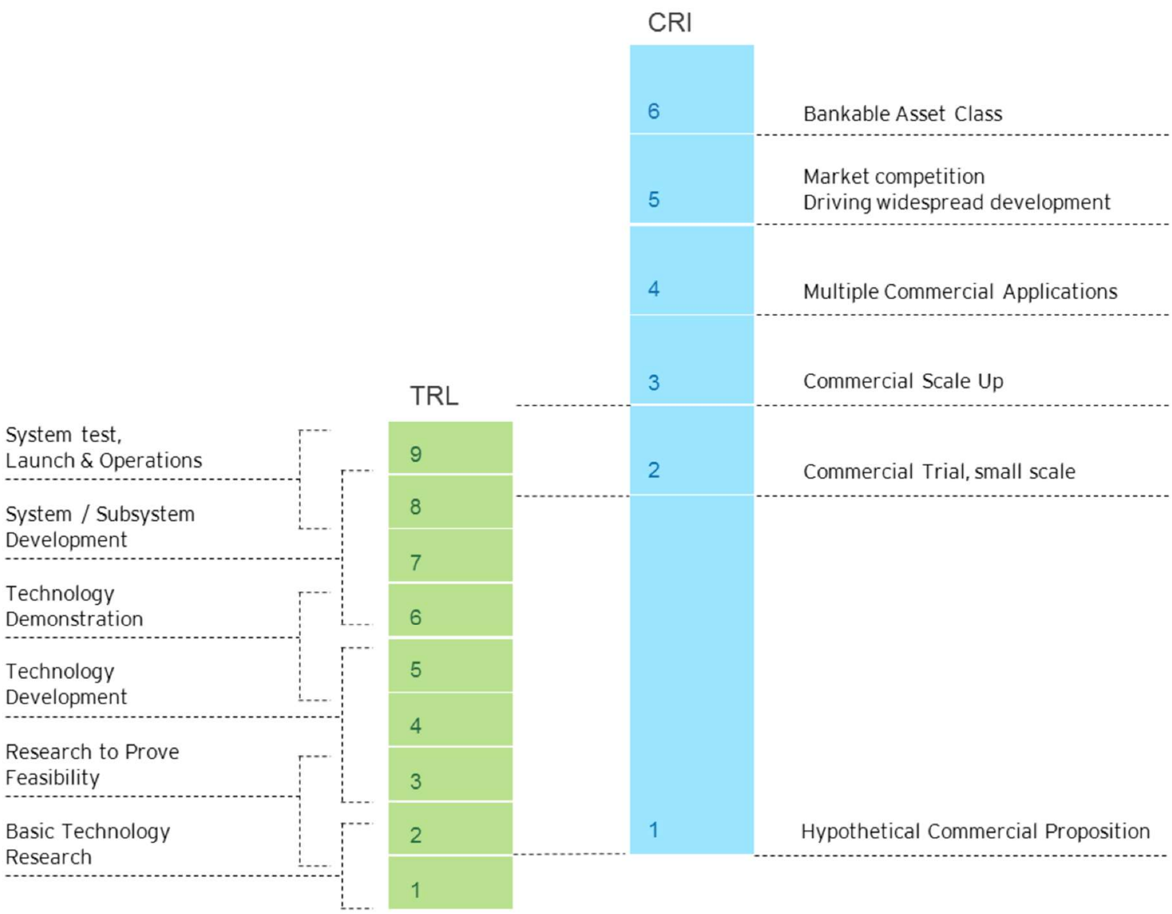


Figure 1-6: TRL and CRL level from ARENA (2014 )

**Measurement and Verification ease**

We discuss the ease with which sequestration by the technology can be measured and verified thus ensuring confidence and trust. Note that the Australian Government has commissioned an independent expert panel to review the integrity of Australian Carbon Credit Units (ACCUs) under the ERF. The Review will consider whether particular methods subject to recent claims – including the human-induced regeneration method – continue to comply with the scheme's integrity standards. This report does not pre-judge the outcomes of the Chubb review.

**Scalability**

Scalability is defined the as the capacity to increase the uptake of technology and the corresponding increase of carbon sequestration through AETs or NETs

**Length of sequestration**

In this report, the likely longevity of sequestration is presented noting that this is different to the often used term permanence, which has a policy rather than a technical definition. Consistent with this being a technical review, here we talk about the likely duration of sequestered carbon as a balance of its turnover rate and risks to stocks.

**Social, environmental impacts, risks, and co-benefits**

This review section identifies potential social or environmental impacts, positive and negative, and co-benefits from scales deployment of NETs and AETs.

**Barriers to implementation:**

These criteria provide a qualitative analysis of the key barriers (non-technical) to uptake and scaling. Sub section for analysis include:

- Policy and regulatory environment:
- Social license and stakeholder acceptance
- Technology performance variability
- Financial proposition and costs and access to capital
- Industry supply chains and skills
- Market opportunities or market creation

**Key research questions:**

This section provides an assessment of gaps in knowledge (including technical) for the potential of a technology to be realised. Research related to overcoming barriers for a technology to provide a pathway to translate potential to economic sequestration are captured.

## 1.5 Technologies reviewed and chapter lead chapter authors.

- **Permanent Plantings**: Stephen Roxburgh (chapter4)
- **Plantation and farm forestry**: Stephen Roxburgh (chapter5)
- **Human induced regeneration of native forest**: Stephen Roxburgh (chapter 6)

- **Avoided land clearing:** Stephen Roxburgh (chapter 7)
- **Savanna burning:** Stephen Roxburgh (chapter 8)
- **Soil carbon:** Michael Battaglia (chapter9)
- **Coastal (mangroves), Blue carbon and Teal Carbon:** Andy Steven (chapter 10)
- **Pyrolysis Biochar:** Lynne MacDonald (chapter 11)
- **Geological storage (CCS):** Allison Hortle (chapter 12)
- **Bioenergy with carbon capture and storage (BECCS)**: Lei Gao (chapter 13)
- **Direct air capture (DAC)**: Paul Feron (chapter 14)
- **$CO_2$ mineralisation (Advanced weathering):** Sandra Occhipiniti (chapter15)

## 1.6 Report Structure

This report is structured as follows. Key findings are found in the next chapter, followed by the roadmap for a national sequestration foresighting and assessment capability in chapter 3. The sequestration technology reviews follow in chapters (4-15).

## 1.7 References


Anderson, K., & Peters, G. (2016). The trouble with negative emissions. Science, 354(6309), 182-183.

ARENA (2014) Technology Readiness Levels for Renewable Energy Sectors. URL : https://arena.gov.au/assets/2014/02/Technology-Readiness-Levels.pdf

IPCC, (2018): Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan,

IPCC, 2022: Climate Change (2022): Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

National Academies of Sciences, Engineering, and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

Honegger, M et al (2017). Climate change, negative emissions and solar radiation management: It is time for an open societal conversation. White Paper by Risk-Dialogue Foundation St.Gallen for the Swiss Federal Office for the Environment.

Minx, J. C et al (2018) Negative Emissions – Part1: Research Landscape and Synthesis, Environ. Res. Lett. 13 063001

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, 389pp.

UNFCCC NDC update, 2022, Australia's nationally determined contribution, communication, https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20NDC%20June%202022%20Update%20%283%29.pdf

# Key Findings

## 2 Key Findings

This section synthesises the technology chapters presented from chapter 4 onwards. The synthesis provides an overarching picture of the current state of sequestration technologies and their outlook. It does this mainly in tabular and figure form with commentary on the key points from these materials. This condensed view of the different technologies, their dependencies, costs, and benefits, provides a quick guide as to the options for a portfolio of technologies to support Australia's national emissions reduction goal.

### 2.1 Technical and Economic potential sequestration

This report provides speculative yet defensible estimates for technical and economic potential sequestration for 2035 and 2050. Estimates are necessarily speculative because, in many cases technologies have not yet started to scale and this process may reveal barriers and competition for resources (especially land) between the technologies. As the imperative for CDR rises and as market prices for carbon rise, innovation may be accelerated and what appears unlikely now may be possible in the future.

This is more likely to impact economic potential estimates than technical potential estimates as the latter are in most cases capped by biophysical limits. A subsequent phase of this project will look at how innovation might reduce some technologies' price per tonne of sequestration. The innovation required can be thought of as a means to translate technical into economic potential sequestration. As mentioned earlier in this report, each of the technologies is reviewed in isolation and the competition between them for resources is not resolved.

The difference between technical potential and actual sequestration as an indicator of opportunity should be viewed with caution. Some of these opportunities (gap) may be closed, but there may be serious technical or economic barriers that cannot be addressed. Similarly, the difference between actual and economic sequestration may overestimate the opportunity in the short term. A better measure of opportunity is the difference between the actual and the realisable sequestration (the latter of which is not calculated in this report). Realisable sequestration is lower than the economic potential sequestration(see chapter 2.1), with the difference in some part due to resource competition and economics. So, for example, the gap in geological storage technology is affected by competition with BECCS for access to the same geological storage. Similarly, realisable sequestration for plantation and farm forestry is affected by competition for the same land base. Marked increases in carbon price or significant cost reductions in the delivered cost per tonne of sequestration from the technologies could also close the gap between realisable and economic potential sequestration. This being stated pending calculations of realisable potential we use economic potential less actual sequestration as a surrogate measure of the opportunity noting it may be an overestimate.

For all but one technology it was possible to find an estimate for technical potential sequestration from existing analyses and publication, but it was more difficult to find figures for economic potential estimates. Economic potential numbers rely on some insight into resource limitations, adoption barriers and plausible market settings. In the short term these are fixed but over longer periods may change. To assist with providing estimates existing ERF settings were often used. It is noted that ERF settings are a relatively conservative framing for economic sequestration, albeit one with a high-level of integrity built into the process.

It is also worth noting that a carbon price of a maximum of \$30 tonne$^{-1}$ of $CO_2$-e was used in Roxburgh et al. (2020) to frame the economic potential numbers and while not inconsistent with the numbers included in the Federal governments modelling (Reputex 2021) could be exceeded if the imperative for climate action increases.

Other institutional framings through voluntary markets or through company insetting into value chains may lead to higher estimates of economic sequestration. The salient point for this report is to observe where the gaps between actual in 2022, economic potential and potential are marked. Where the gap between these estimates is large it points to an area of opportunity where reframing regulation, changing incentives or building alignment to co-benefits may unlock significant national sequestration opportunity.

Unlocking all this opportunity may not be possible however as the economic or resources required to scale to that extent may be improbable. To indicate where opportunities might exist, the gap between economic potential and actual sequestration can be seen in Figure 2-2. As mentioned in the introduction, the best estimate of opportunity will be the difference between realisable and actual sequestration.

The greatest technical potential for sequestration is geological storage, with 233 Gt. Note that for geological storage, a storage total is provided as annual estimates are unavailable. It was not possible to find estimates for geological storage for 2050, but if we total the projects in development, an estimate for 2035 would be ~24Mt $y^{-1}$. All these projects would likely still be operational by 2050 (ERF Methodology allows for 25 years of operation, with options for project expansion). The economic sequestration for geological storage would increase significantly if BECCS and/or DAC projects are economically viable by this time, adding at least an estimated further 28-35 Mt $y^{-1}$ for a total of ~55 Mt $y^{-1}$. 55 Mt $y^{-1}$ is well below the geological storage technical potential of 233 Gt. The addition of BECCS and CCS economic potential estimates, is reasonable in this case and useful to understand scaling trajectories.

It is important to note the relative rate of storage of the different technologies. The Gorgon project, although not without setbacks, has stored 6.6 Mt of CO2 since becoming operational in August 2019.

Many of the nature-based solutions have good technical potential for sequestration, particularly permanent plantings, plantation and farm forestry, and soil carbon with potential of 480Mt $y^{-1}$, 631Mt $y^{-1}$ and 115 Mt $y^{-1}$ respectively by 2050. The gap between actual and economic potential in all these technologies is still large. Uptake has been high in nature-based technologies due to their high technology readiness levels and policy support through the carbon farming initiative and the Emissions Reduction fund and they have produced 12.39M ACCUs to date. The ERF fund has acted to accelerate the CRL of these technologies and driven by the high potential and the supportive policy position, significant investment into these technologies (especially soil carbon) has flowed. The absolute gap between technical potential and economic potential sequestration for plantation forestry and permanent plantings is still high and presents an opportunity to close.

Not surprisingly there is a strong relationship between cost per tonne of sequestration and commercial readiness level. Where costs are high projects are not being developed. Biochar, BECCS and Direct Air Capture have significant sequestration potential but have high costs. These are areas where investment into research to bring down the unit cost associated with capture could increase national sequestration potential. If early-stage projects such as biochar or BECCS projects could be aligned to other areas of co-benefit such as supporting afforestation in areas in need of hydrological rebalance or producing products that could be embedded in downstream industries (such as biochar into plastics) then this may help create co-funding opportunities. The anomaly to this is geological sequestration where it appears sequestration costs are low and yet CRL is also low. Review suggests the barriers here are different, high initial capital costs and regulatory barriers. Approaches to unlocking the potential of this opportunity is different and involves processes to de-risk investment (underpinning knowledge infrastructure that shows where prospective sinks might be) and potentially concessional loans or forward contracts on sequestration to offset the high initial investment.

It is not possible at this stage to provide estimates for 2035 for many of the technologies as the modelling has not been done. In some ways it is easier to forecast estimates for 2050 rather than 2035.  Observation from the uptake of ERF technologies such as avoided deforestation and soil carbon show that where prices of carbon exceed price of project delivery by some margin (and perhaps a hurdle rate of 1.2 to 1.5 for land use change) then we see resources and capacity for project creation build rapidly. Even then though there are limits as was seen for example during the Managed Investment Scheme forestry plantation expansion, where at its peak when demand exceeded supply, maximum planting rates were constrained to around 100,000 ha by seed and seedling supply and labour in regional areas where projects were targeted.

Notwithstanding that without more comprehensive integrated modelling it is not possible to accurately quantify the 2050 potential and economic sequestration opportunities.

The nature-based solutions have the opportunity to deliver between 90 and 114 Mt yr-1 by 2050 if all economic sequestration opportunities are realised (it is assumed that permanent plantings and plantation forestry are 100% competitive, and that there is no feedback from land use competition and scaling, and new demand demands for feedstocks don't adversely affect the scalability) at a price of $30 per tonne. As discussed below attaining this sequestration will require work to overcome barriers and to increase the enablers and incentives for project development  As already stated the better guide to  opportunity is realisable less actual potential which will be less than the numbers described here.

Another pertinent point is that most nature-based solutions saturate – that is storage will increase and eventually slow and stop as forests grow to maturity or soils reach their new equilibrium soil carbon value. The annual sequestration figures describe here will last for 15-40 years or so and then cease.  This needs to be factored into emissions reduction pathways and can be planned for when designing a portfolio of approaches.

| Sequestration Potential | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Technology** | **2021-22** | **2035** | **2050** | | | | **Notes** |
| | **Actual (Mt.yr-1)** | **Economic (Mt.yr-1)** | **Economic (Mt.yr-1)** | **Cost ($.t-1)** | **TRL** | **CRL** | |
| **Permanent Plantings** | ~0.5[1]<br>2.1[2] | | 16 | 20-30 | 9 | 4-5 | ERF methodology and FullCAM modelling, 25 yr annual average |
| **Plantation and farm forestry** | ~0.1[1]<br>11.5[3] | | 32<br>(0.6) | 10-30 | 9 | 4-5 | ERF methodology and FullCAM modelling, 25 yr annual average<br>Farm forestry in parentheses |
| **Human induced regeneration of native forest** | 6.4[1]<br>20[2] | | 39 | ~5 | 9 | 5-6 | ERF methodology and FullCAM modelling, 25 yr annual average |
| **Avoided clearing** | 2.3[1] | | ~8 | 5-10 | 9 | 2-3 | ERF methodology and FullCAM modelling, 25 yr annual average |
| **Savanna fire management** | 1.46[1]<br>5.6[4] | | 6 | 5 | 9 | 3-5 | |
| **Soil Carbon** | 0[1] | 5-29 | 5-29 | 7-13 | 9 | 3-4 | Competition between practices makes exact outcome hard |
| **Blue and Teal Carbon** | 1.1[6] | | No estimate | 18-30 | 9 | 3-4 | Serrano et al 2019 |
| **Pyrolysis Biochar** | 0 | | No estimate | 80-120 | 9 | 2-4 | [2]estimated as theoretical potential |
| **Geological storage** | 2.26 – (Gorgon project 2020-21) | ~24* | >50 | 14-35 | 9 | 4-5 | Small exemplars given in the order of >5 Mt per year<br>*Based on current pipeline, all would be still operational by 2050 with more likely to come online (esp. if BECCS and DAC become economic) |
| **Bioenergy Carbon capture and storage[5]** | No estimate | | 25-38 | 100 | 2-9 | 2 | DISER 2021b, Pour et al 2018. TRL level depends on biomass feedstock and conversion route, energy form and CCS technology. |
| **Direct air capture[5]** | No estimate | | No estimate | 300-600 | 4-7 | | Uptake dependant on technology cost and electricity cost. Enabling technology rather than sequestration |
| **Mineral carbonation/ advanced weathering** | 0.1 | | No estimate | 28-300 | 5-7 | 1 | Ni mining ~16Mt per year<br>Au mining ~16Mt per year |

**Table 2-1: Summary of technology potential. [3]Depending on technology selected. Note where no value is provided, there is insufficient data or evidence for inclusion.[1] ACCUS' issued 2021-2022 extracted from the ERF project register July 2022. [2]AEGIS 2010-2020 includes soil carbon as well as living biomass and forest debris. [3] AEGIS 2010-2020 includes soil carbon as well as living biomass and forest debris but excludes harvested wood products.[4]AEGIS 2016-2020 includes biomass, debris and soil carbon. [5]Both Bioenergy and direct air capture use geological storage for sequestration. [6]AEGIS 2010-2020 includes soil carbon as well as living biomass and debris.**

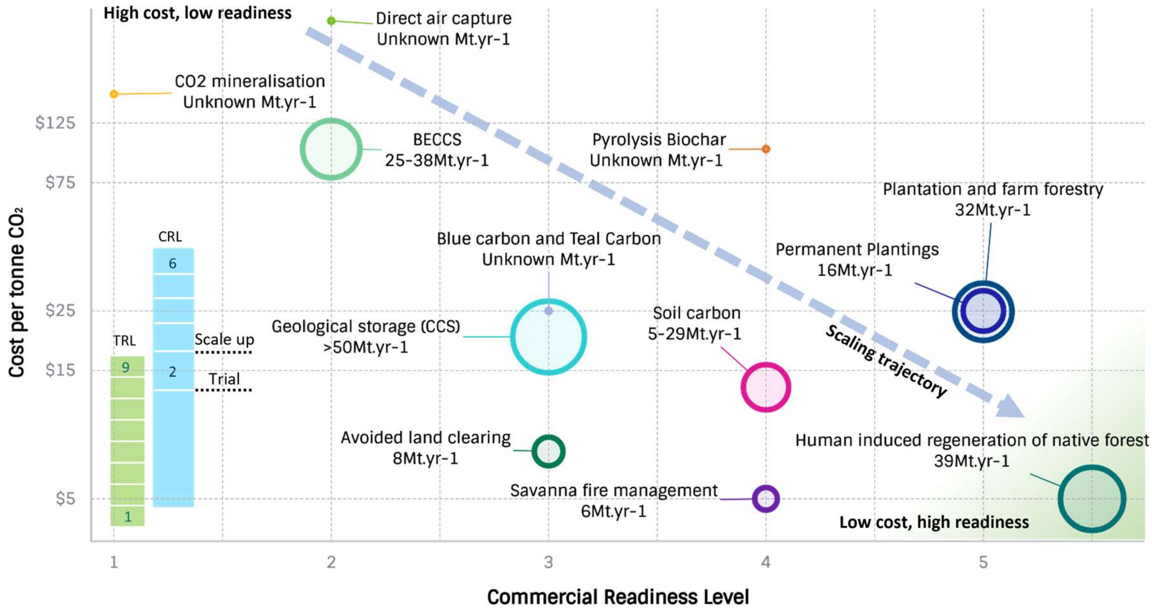



**Figure 2-1: Summary of economic sequestration. BECCS is a subset of CCS, and totals cannot be aggregated.**

Figure 2-1 is a summary diagram of economic sequestration. The volume of sequestration is displayed by the size of the disc, with the x-axis representing the commercial readiness level and the y-axis representing the cost of sequestration in dollars per tonne. All estimates are for 2050, unless otherwise noted and where an estimate is not made it is indicated as unknown. An interesting aspect of this diagram is that it allows the scaling trajectory to be identified. The scaling trajectory is the diagonal blue arrow, which represents the scaling path of a technology, moving from low CRL and high cost in the upper left corner, to high CRL and low cost on the lower right-hand corner.

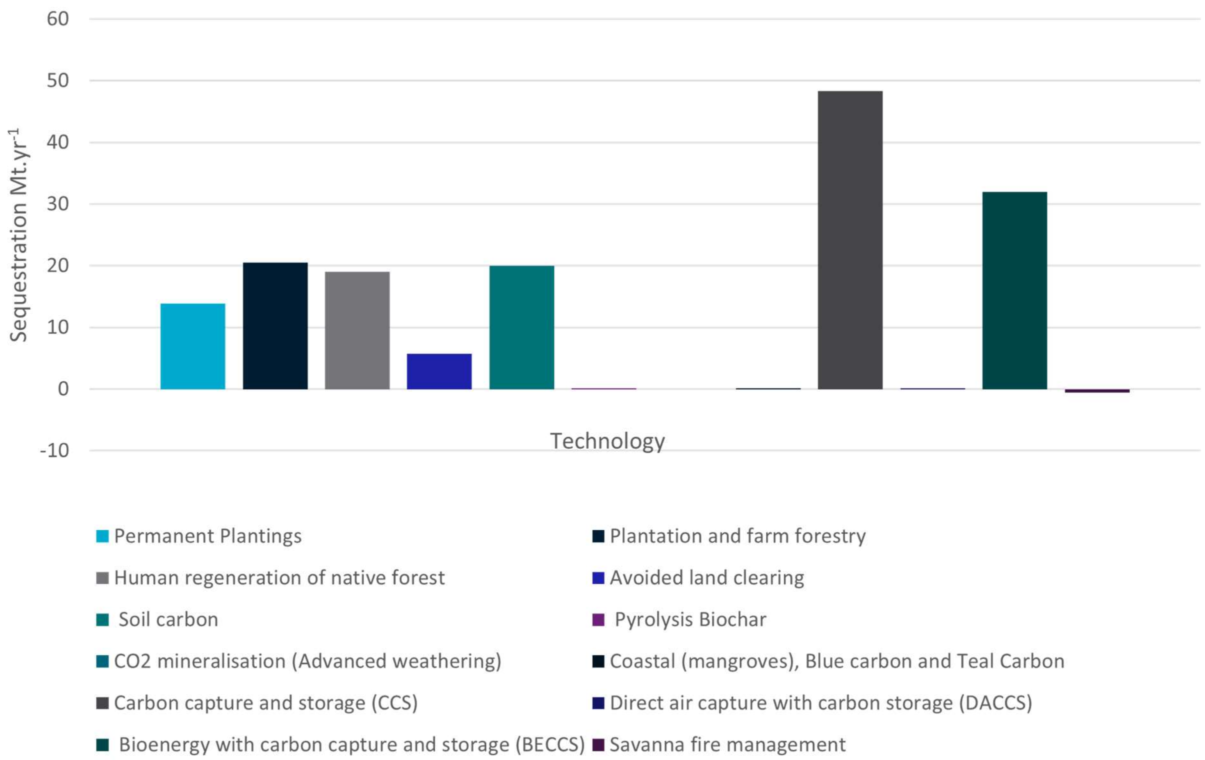


Figure 2-2:Economic less actual sequestration. Where economic or actual sequestration is unknown, it is set to zero.

In Figure 2-2 above the difference between technical potential and economic sequestration is shown representing the 'gap' or opportunity for the technology. As is noted in 1.4, the real opportunity is the difference between actual and realisable sequestration, which is not available as realisable sequestration estimates are not available.

## 2.2 Competition for land, water, energy, and geological storage.

All the nature-based technologies compete for land and water use to varying degrees. BECCS and biochar compete for biomass and CCS and BECCS compete for geological storage. CCS, DAC, and mineral carbonation are competing for energy and water. Emerging demands for biomass feedstocks into other areas of avoided emissions and the bioeconomy, such as the use of charcoal as an alternative to coal in smelting processes, the use of biomass for future plastics industries and the rise of a biogenic sustainable aviation fuel will impact on the economics of scaling for these technologies.

As discussed above and in more detail in 1.4, the technologies have been reviewed independently. Each of the technologies requires resources to provide sequestration. How the resources are ultimately distributed between competing demands to achieve highest and best use is a question that remains outstanding.

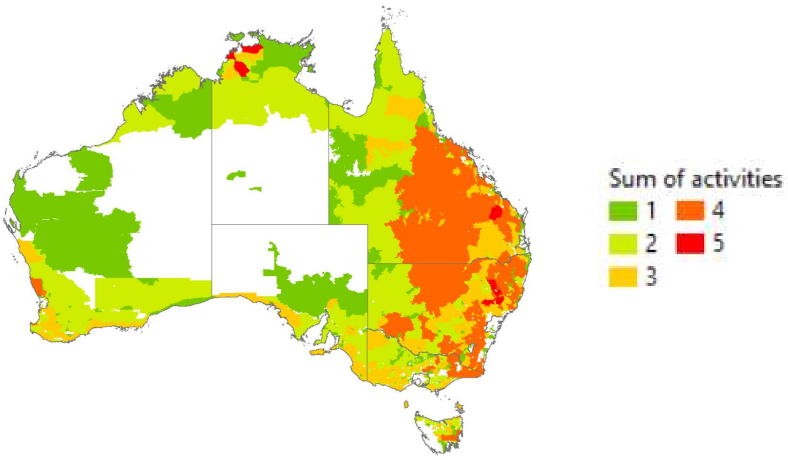



Figure 2-3: Summary of spatial technical sequestration for a range of nature-based technologies. The maps are aggregated to SA2 level.

In Figure 2-3 above the overlaid potentials from the nature-based method are displayed, with a simple addition of layers being the sum of activities. Red and orange signify areas land use overlap, indicating high competition for land use.

These results above are possible due to the prior work of Roxburgh et al, 2020.

## 2.3 Enablers, barriers, and scaling

### 2.3.1 Enablers

There are co-benefits associated with many of the technologies that can be leveraged to assist uptake and scaling. Providing supporting information on the economic benefits and the context in which they will be realised may assist uptake. Allowing market mechanisms that encourage benefit stacking (where multiple payments can be paid for the same activity that is delivering a range of positive outcomes) to improve the overall value proposition of technology implementation will assist.

For most of the nature-based technologies further assessment of the benefits, co-benefits and costs as well as better understanding the land use trade-offs could support scaling.

Innovative market mechanisms that allow small holders to participate as well as allowing trade of offsets where multiple benefits are recognised, could increase supply off offsets and support scaling of nature-based technologies.

Some technologies require proximity to concentrated feedstocks (BECCS, Biochar) or proximity to those who will use products (biochar, $CO_2$ captured by DAC for mineral carbonation or geological storage). Coordination between industry and government can assist in scaling such industries.

As many of the opportunities for sequestration are in regional areas, regional benefits of the technologies are critical to achieve social license to operate, uptake and the scaling required to realise the transition potential into economic sequestration. Further, regional opportunities will require suitable supply chains and logistics at low cost to enable and support those sequestration activities

**Table 2-2: Enablers and barriers to technology scaling**

| Technology | Enablers | Barriers |
|---|---|---|
| **Permanent Plantings** | Increase volume and reduce cost of seeds or tube stock. Expansion of skilled workforce . Further quantification of co-benefits in agricultural landscape to incentivise uptake. Stacking environmental services payments to improve economics | Economics – high cost of implementation. Misalignment of incentives with costs of longevity. Availability of suitable land and potential conflicts over water use and competition with agricultural production. Significant expansion can change regional economies and employment. Climate change risk |
| **Plantation and Farm Forestry** | Innovative market creation for wood-based products including for bioenergy and biochar. Better quantification of co-benefits to support uptake and social license. Innovative methods for cost reduction to improve the economics and uptake. | Economics – high cost of implementation. Misalignment of incentives with costs of longevity. Availability of suitable land and potential conflicts over water use and competition with agricultural production. Significant expansion can change regional economies and employment. Cost/economics and availability of suitable land. Supply chain costs. Capital for processing plants. Climate change risk, |
| **Human induced regeneration of native forest** | Targeted investigation of social and environmental impacts and risk. Further economic analysis to better quantify life cycle costs | Concern about sequestration rates and length of storage particularly risks with climate change. Changes to traditional land use. |
| **Avoided land clearing** | Stacking environmental service payments to improve economics. Reduced regulatory complexities. | Competing land use opportunities and changes to traditional land use. |
| **Savanna fire management** | Alignment with social co-benefits. Further exploration of barriers to uptake. | Area of land suitable for activity limits the uptake. Possible reluctance to commit to maintaining for 25 years. |
| **Soil carbon** | A clear articulation of benefits to productivity; Novel approaches to increasing soil carbon stocks; and reduced measurement and verification costs | Cost of measurement and the need to maintain the carbon stock into the future are key barriers. There is a risk of reversal with climate change. Upfront costs and slow returns over extended periods present a cash flow disincentive. |
| **Blue and Teal Carbon** | Identification of feasible areas for blue carbon, better estimates of sequestration rates and length of storage, inclusion of sediment sequestration | Complex land tenure arrangements and permitting process. Poor estimates of technical sequestration. |
| **Pyrolysis Biochar** | Innovative business models to support uptake. Policy incentives to drive industry investment. Better estimates of lifecycle costs. | Costly and complex logistics and supply chains. Competition for land and water resources. A need for social licence. |

| | | |
|---|---|---|
| **CCS** | Investment in exemplars. Information on potential scale of containing reservoirs. Long forward contracts to de-risk upfront investment | Permitting and regulatory complexities. High upfront capital costs. Contested social licence. Timeframes for development. |
| **BECCS** | Close and assured feedstock supply. Off-take agreements for products | Costs and economics of the technology. |
| **DAC** | Low cost, low-emission-energy and access to water. Compared with some other sequestration options has a low land footprint: 100x less than afforestation for example for same unit sequestration | Costs, regulatory and policy environment, ability to assess uptake options from a socio-techno- economic perspective |
| **Mineral carbonation and advance weathering** | Improved knowledge of sequestration rates; low cost emission free energy to drive pumping of CO2 into, or turning of tailings to increase sequestration rate | Cost/economics and availability of suitable land; supply of tailings of suitable geological character |

### 2.3.2 Barriers

Cost per unit of sequestration remains a barrier for some technologies. This has been discussed above but where technologies have high unit sequestration cost but also high potential and economic sequestration opportunity investment in research, development, and extension (extension in the broadest sense of commercial trialling and business model development) may be a useful strategy. The same applies in many cases to barriers imposed by measurement cost. Innovative approaches to MRV may assist, as will the development of common underpinning knowledge infrastructure that can drive new approaches to MRV (such as the Federal Government investment into digital soil infrastructure to support next generation space-time soil carbon modelling).

In a few cases regulatory barriers present a hurdle. As technologies are increasingly implemented and clarity of risks and outcomes of scaling become apparent these may dissipate. Early-stage engagement with project proponents, regulators and community may expose risks and sticking points that may lead to quicker resolution of barriers.

## 2.4 Length of Storage, Measurement, and verification

| Technology | Length of Storage (yr) | Measurement and Verification |
|---|---|---|
| **Permanent Plantings** | 25-100 | Can be routinely assessed indirectly by remote sensing and is readily observable from the ground. |
| **Plantation and Farm Forestry** | 25-100 | Can be routinely assessed by remote sensing and is readily observable from the ground. |
| **Human induced regeneration of native forest** | 25-100 | Can be routinely assessed by remote sensing and is readily observable from the ground. |
| **Avoided land clearing** | 25-100 | Can be routinely assessed by remote sensing. |
| **Savanna fire management** | ~25 | Has well established measurement and verification protocols. |
| **Soil carbon** | ~25 | Measurement of SOC is currently costly, with a goal in LETS[4]to reduce from $30 to $3 per ha. |
| **Blue and Teal Carbon** | 25-100 | Some research for default estimates, but sequestration can be estimated using remote sensing. |
| **Pyrolysis Biochar** | 300-600 | EU – rate of potential decomposition is available as a guide. In Aust using ERF soil measurement methodology for biochar in soil provides some estimates. |

[4] LOW EMISSIONS TECHNOLOGY STATEMENT 2021 (dcceew.gov.au)

| | | |
|---|---|---|
| **Geological storage** | > 1,000,000 | Highly precise for transport, injection, and quantification of storage volumes, requires indirect methods for ongoing plume monitoring. Well established tools and techniques. |
| **BECCS** | See CCS above | See Geological storage above. |
| **DAC** | Not provided as this is a capture technology. | Simple and precise for capture. |
| **Mineral carbonation and advanced weathering** | >1000 years | Rates of carbon uptake are well known, and mineral carbonisation can be routinely measured in a laboratory. |

**Table 2-3: Scalability, Length of Storage and Measurement and Verification Summary**

### 2.4.1 Length of storage

Nature-based technologies have lower length of storage than geological storage options, but they provide most of the low cost, readily scalable options. Most of the technologies have strong co-benefits streams associated with them around regional employment and multi-purpose land use. Many nature-based technologies are associated with risks from climate change, and all face some degree of social license to operate pressure. The impacts of climate change on the nature-based technologies are difficult to predict and may have positive benefits for some or in some areas, not in others.

## 2.5 Risks and co-benefits

| Technology | Social and environment risks | Co benefits |
|---|---|---|
| **Permanent Plantings** | Climate risk, natural events – fire and drought are key risks. Disruption to existing land use and land competition are also risks. Environmental risk with increased water use. | Co-benefits include improved biodiversity, soil health, reduced erosion, and climate resilience. Provides additional income stream to land holders. |
| **Plantation and Farm Forestry** | Climate risk, natural events – fire and drought are key risks. Disruption to existing land use and land competition are also risks. Impacts on water resources. Increased fuel load and fire risk. Forests are susceptible to pest and disease affecting sequestration rates. | Co-benefits include improved biodiversity, soil health, reduced erosion, and climate resilience. |
| **Human induced regeneration of native forest** | Climate risk and natural events – fire and drought are risks. Disruption to existing land use and potential for increased exotic species are risks. | Biodiversity conservation outcomes, other environmental amenity, including improved soil health. Can increase farm profitability by providing alternative income stream. |
| **Avoided land clearing** | May impact on other land use options such as increased pastoral land. Potential for increased fire risk | Co-benefits can include improved biodiversity, soil health and climate resilience. Can provide an alternative income stream. |
| **Savanna fire management** | Limited land management options due to need to maintain sequestration. | Livelihoods, indigenous socio-economic benefits, appropriately managed biodiversity outcomes. |
| **Soil carbon** | Places an onus on future land managers to maintain. Is reliant on maintaining primary productivity, so is subject to climate risk. | Improved soil carbon has benefits ranging from improved soil health, farm productivity, improved biodiversity, and improved farm resilience. |

| | | |
|---|---|---|
| **Blue and Teal Carbon** | The major social risk relates to land ownership and lack of indigenous engagement. Limited land management options due to need to maintain sequestration. | Multiple co-benefits, fisheries, pollutant removal, coastal protection, ecosystem services, indigenous values. |
| **Pyrolysis Biochar** | Social consideration relates to implication of land use trade-off and community acceptance | Can provide input source for secondary industries. Soil amendment and improved soil health2 |
| **CCS** | Requires social license for establishment, concerns related to $CO_2$ leakage and GW contamination. | Can provide input source for secondary industries; regional employment; small surface footprint means site can be shared by multiple users, grazing, etc. |
| **DAC** | Localised impact on land and water use. | Can provide input source for secondary industries |
| **BECCS** | Competition for land and water resources, social risks associated with change of land use. Could have ecological risks associated with biomass and water supply. | Depends on the source of biomass. |
| **Mineral carbonation/ advanced weather** | Ex-Situ carbonation, risk of possible harmful by products.<br>In-Situ: Potential for localised increased seismicity and groundwater contamination. | Makes use of mine tailings as a value stream |

**Table 2-4: Summary of Social and Environmental risks, Co-benefits, and Barriers.**

The transition to net zero is but one of the many challenges that society needs to confront. The ability to generate co-benefits from sequestration activities, or conversely carbon positive outcomes from the pursuit of other critical objectives, will be crucial for efficient and expeditious response. Nature-based solutions and carbon markets have been suggested as having transformative capability for the Australian landscapes (after the Garnaut 2008). This report shows that there are substantial opportunities to increase greenhouse gas removal via forestry activities, avoided deforestation, increasing soil carbon stocks and into the future options in blue and teal carbon. All nature-based technologies can offer environmental and, in some cases, social benefits. There is, as previously discussed, an opportunity through payment for delivery of these other benefits to increase the economics of scaling some of the sequestration technologies, and efficiently meeting multiple societal needs. The Land Restoration Fund in Queensland is one example of this approach.

However, poorly designed landscape change can have adverse outcomes. Existing regulation is in place to control this, for example the rainfall limit on afforestation.  These controls will be designed in the light of the best knowledge at the time but need constant re-evaluation as the technologies are scale and the effects of their uptake on environmental or social amenity become more apparent. If we successfully scale these technologies, a monitoring and evaluation program that evaluates the physical and social landscape change should be implemented.

Many of the technologies will be embedded in regions, providing opportunities to create new sources of economic activity or to create inputs into new industries. This is already emerging in some cases such as the Barcaldine Renewable Energy Zone which is looking to bring together a range of sequestration options, avoided emission activities and new industries to create regional prosperity (Sunshot Industries 2021, https://sunshotindustries.com.au/brez).

A key emerging issue is that competition is emerging for the feedstocks and land (and water resources) that we might initially think are available for generating sequestration.  There is already planning underway for a biogenic aviation fuel resource to fill the gap in the sustainable aviation fuel pathway before the development and scaling of hydrogen generated fuels in the next decade. The development of a “green” steel industry will require alternatives to coke for smelting and may look to woody biomass as a source of charcoal.

## 2.6 Opportunity for Australia

This report is a stocktake of current knowledge on a range of technology options to sequester carbon for Australia. The best estimates for the potential and economic sequestration have been assembled coupled with a compendium of co-benefits, enablers, barriers and risks. This knowledge is insufficient to provide a clear view of the opportunity for Australia, rather it provides an indication and an input to a more complete integrated modelling task to assess the various options and opportunities. This work is detailed more fully in chapter 3.

Not withstanding the above, it appears Australia has good opportunities to sequester carbon via a range of technologies. Each of those technologies alone is not sufficient to provide a pathway to Australia's emissions reduction target. Rather a portfolio approach combining the best set of technologies will be required.

Australia is well positioned with abundant land-resources, significant geological storage capacity and low-emission-energy resource potential (Campey et al, 2017), to translate the potential identified into realisable sequestration.

There are many potential pathways for the use of $CO_2$ once captured either from Direct Air Capture of point sources of $CO_2$. These pathways include $CO_2$ use in many high-value long-lived products (e.g. cement), which ultimately present opportunities and options for Australia. These pathways are well covered in the CSIRO $CO_2$ utilisation roadmap (Srinivasan et al, 2021) and consequently not covered in this report.

In addition, Australia has a well developed carbon market which is a necessary institutional structure to support the scaling of these technologies. Further, Australia has good underpinning knowledge infrastructure (such as the national soil grid and downscaled meteorological data and modelling frameworks such as FULLCAM). We possess a skilled, digitally enabled workforce to take advantage of advanced methods to target opportunities in the most prospective areas and conduct sound risk analyses to de-risk investments.

Within Australia, research strength and capacity can be leveraged to explore relevant technologies. There is also a strong financial sector with large managed funds that can drive funds into low emissions technologies, sustainable industries, and land management. Public policy has supported this latter strength by creating public investment funds such as the Clean Energy Finance Corporation, which has acted as an early investor to de-risk later investments by the broader financial sector.

The portfolio of sequestration options we select as a society will be a combination of technologies, and it should be designed with an awareness of risk and the longevity of technologies. Understanding what this means for future pathway options in terms of sink saturation and the requirement for timing of emissions reductions compared with offsetting is also required.

Dependencies exist between technologies with some needing a common shared finite resource such as water and biomass (e.g., BECCS and Biochar). Achieving efficiency in achieving national emissions reduction targets can be improved through a purposeful allocation of these resources between competing demands to achieve highest and best use. Building analytic capacity to resolve these matters should be a priority, and is discussed in more detail in chapter 3.

Technologies are at different levels of technical maturity and are evolving with investment and trialling at different rates. Key levers that affect technology scaling such as the development of competing industries (e.g., Sustainable Aviation Fuel) similarly affect the scaling rates. The scaling trajectories are dynamic and require the analysis to be done at regular repeated intervals if a best set of technology options is to be developed, that is the analysis cannot be presumed to lead to a 'set and forget' strategy.

In the face of high uncertainty associated with scaling emerging sets of technology, a process of both monitoring and evaluating outcomes, and an ability to recalibrate the negative emissions technology strategy in the light of changing circumstances and evidence is required.

## 2.7 Chapter References


Campey, T., Bruce, S., Yankos, T.*, Hayward, J., Graham, P., Reedman, L., Brinsmead, T., Deverell, J. (2017) Low Emissions Technology Roadmap. CSIRO, Australia.

Garnaut, R. 2008. The Garnaut climate change review: final report. Garnaut Climate Change Review. https://apo.org.au/node/3028

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report.

Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) CO2 Utilisation Roadmap. CSIRO

Sunshot Industries (2021) Barcaldine Renewable Energy Zone A model for regions in transition. Report available at Link to Report

# Roadmap

## 3 Roadmap for national capability for recurrent and targeted assessment of negative emissions technology supply

### 3.1 What is a national capability?

Maintaining strong economic growth in an internationally competitive environment while transitioning to net zero emissions represents a significant challenge for global economies. As part of the global effort to reach net zero emissions and to meet future Australia's Nationally Determined Contributions, rapid decarbonisation and provision of negative emissions will be required.

Australia has significant potential to develop new and transition existing industries to provide negative emissions, particularly in areas of new and emerging technologies. As this report highlights, there are no silver bullets, and no single technology appears to be able to deliver all of Australia's current and future sequestration capacity. Instead, Australia must make informed decisions on what sets of technologies can and should be deployed, in which regions, and the implications, trade-offs and opportunities for these regions economically, socially, and environmentally need to be well understood. This also needs to account for the current and future impacts of climate variability and change that have significant implications for resource availability (e.g. food, water, and energy). Furthermore, this cannot be done in isolation from the transition from fossil fuel to renewable energy systems such as hydrogen and solar.

Developing the national capability to support the provision of negative emissions as part of Australia's Nationally Determined Contributions requires a modelling capability underpinned by innovations in emerging technologies in an integrated assessment modelling (IAM) approach. This approach represents the coupling and feedback between economics and the earth system (climate and carbon cycle). This represents the next generation of modelling systems beyond those developed and used for Australian National Outlook Reports, which have focussed on the economic pathways and not considered regional impacts of climate change and variability on the current and future supply sequestration capacity.

#### 3.1.1 A new national modelling capability

At the heart of this new national capability are two global models:

1. The Global Trade and Environment Model (GTEM) is a global-scale multisector dynamic Computable General Equilibrium (CGE) model designed to analyse economic trade-offs associated with the production and use of emissions. It represents a careful representation of regions and economic activities that are most relevant to climate change, carbon, and energy transformation. It has a detailed accounting of commodity-embedded energy flows and positive and negative emissions.
2. The Australian Community Climate and Earth System Simulator (ACCESS). ACCESS is a model that couples the climate to the carbon cycle to simulate weather and climate on a scale from days to

centuries, including extremes. It includes a representation of the land, ocean, and atmosphere interactively coupled to the biosphere and contains all the major $CO_2$ and non-$CO_2$ Greenhouse Gases. ACCESS is a state-of-the-art earth system used extensively in the most recent IPCC AR6 Reports to explore the response of the earth system to different emissions pathways.

Coupling these models allows us to explore and quantify national and regional resource trade-offs (e.g., land-use, energy, water) and feedbacks of different portfolios of negative emissions and quantify the efficacy, benefits, co-benefits, and risk over time. It also provides the capacity to deliver optimised negative emissions portfolios that account for different emissions trajectories and pathways, policy settings, risk appetite and resource constraints. In addition, explore the efficacy of new policy levers and incentives to deliver their intended outcomes, and ask *what if*? Traditionally studies and reports that have explored this transition have focussed on the economic pathways and largely ignored the regional impacts of climate change and variability on negative emissions technologies.

## 3.2 Gap Analysis

This report focuses on a number of mature and emerging technologies and explores the potential and economic sequestration of each approach and highlights the important role that individual negative emissions may play in reducing atmospheric $CO_2$ now and in the future. Understanding the realisable potential of each approach will require addressing key knowledge gaps before they can be integrated into a net zero transition system, these gaps include:

### 3.2.1 Technological Advancement

Despite some of these technologies being mature, for most significant questions remain around permanence, cost, and scalability. Furthermore, what the MRV (Monitoring, Reporting and Verification) requirements, costs and capability are also important considerations.

This report represents an essential first step toward mapping and understanding the current capability of individual technologies, what will be needed in future, and the current barriers to scale for current negative emissions technologies. Examples of the specific gaps for each approach can include:

1. Quantifying the inputs, outputs and dependencies required;
2. A clearer understanding of technology and commercial readiness i.e. current status and timelines for possible deployment;
3. Environmental benefits and co-benefits;
4. Risks (climate and economic) and assumptions;
5. Legal and governance structures (state, national and international, where relevant);
6. Costs and supply chain requirements including Techno-Economic Analysis (TEA) and Life Cycle Analysis (LCA),
7. Any other specific considerations, including links to existing industries, workforce and additional resources needed

Given the pace and growing investment in negative emissions technologies this information will require both regular updating and tech scanning (at least bi-annually). This will allow emerging technologies and their potential to be included, as well as the many commercial-in-confidence technologies under development nationally and internationally.

### 3.2.2 Portfolio Development

Australia faces the challenge of its increasing population requiring food security (domestic and international), demand for clean energy and resources, enhanced health and well-being and conserving and sustainably using water and biodiversity. Traditionally food security, demand for clean energy and resources, enhanced health and well-being, and conserving and sustainably using water and biodiversity have been addressed at the sectoral level. To fully and comprehensively evaluate NETs a whole-of-systems approach is needed to support policy development and decision making.

Developing a portfolio of approaches to supply negative emissions cannot be achieved by summing the potential of individual approaches. In many cases there will be competition between land and resources between approaches at the regional scale. Key to exploring the development of an optimised portfolio is to view negative emissions technologies through a series of interconnected lenses:

1. Social Considerations,
2. Technological Considerations;
3. Economic and Regulatory Considerations; and
4. Earth System Considerations.

This framing is adapted from an integrated systems-wide approach or an integrated assessment modelling framework. While focus need to be on Australia and its regions, it will need to be explored in the context of international developments.

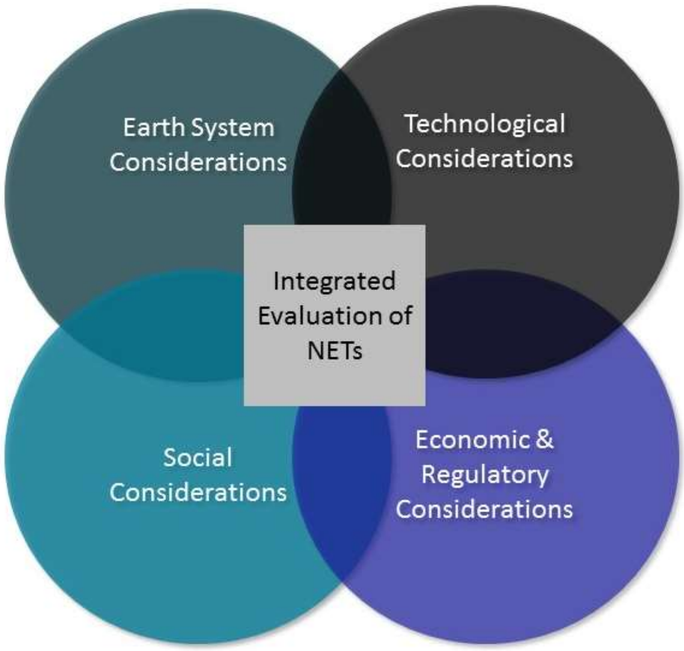



**Figure 3.1 Lenses for the integrated evaluation framework of NETs, exploring the interconnected social, economic and regulatory, technological and earth system feedback between these.**

Within this framing, the social, technological, economic and regulatory, and earth system considerations will need to be explored:

### 3.2.3 Social Considerations.

- Where are the basic NETs resources located, and what are the competing interests on these resources?
- How fast can NETs be implemented?
- What are the disruption and continuity of employment opportunities of NETs?
- Within the context of a transition to a low carbon economy, how do NETs change household welfare and access to other goods?
- What are the opportunities and risks associated with NETs regarding energy, food, and water security?
- What governance structures are required for the effective delivery and regulation of NETs?
- Where are NETs most feasible, and how do they impact/relate to local communities?
- What are the implications of NETs on regional development?
- What are the perceived risks (by the public) for NETs, and how can they be mitigated?
- Are there social risks to Australia if other countries apply these technologies in our region?
- How would deploying NETs impact first nations people and their traditional practices and culture?
- What social and community engagement would be needed to ensure that NETs had widespread trust and support if implemented?
- What are the social costs and benefits of deploying NETs in the Australian context?
- Can we identify and anticipate the issues needed to be addressed to allow the social license to be granted, particularly among transitional rights holders?
- Are there other public barriers to the acceptance of NETs?

### 3.2.4 Technological Considerations.

- What opportunities are there for Australia to contribute to the technological development and assessment of NETs?
- What is the size of the potential contribution of each NETs approach?
- What is the technical feasibility of different NETs?
- What is the potential of different NETs and the synergies between different NETs technologies/approaches?
- What systems are available to verify the sequestration of NETs, and their continued storage?
- Under what settings would different NETs be feasible and scalable?
- What are the barriers to industry and research engagement within Australia?
- What is the deployment and scalability profile of the various NETs?
- What deployment strategies are available for the various NETs?
- What does the research to operation (R2O) pipeline look like to move NETs from theory to development, control trials, and implementation?

- What incentives and barriers are there to sharing information (and IP) around NETs?
- Can we support trade and develop international partnerships to deliver regional solutions though the exploration of NETs or permanent sequestration of $CO_2$?

### 3.2.5 Economic and Regulatory Considerations.

- What are the economic opportunities for Australia in negative emissions?
- Within the Australian context, what existing and new infrastructure is required to support NETs?
- How do NETs impact energy demand and energy production systems?
- What are the environmental, social and economic costs and benefits (including no regrets and co-benefits) of implementing NETs in the Australian context? Are there economic risks to Australia if other countries decide to apply these technologies in our region?
- What regulatory and governance mechanisms would be needed to ensure NETs are deployed safely and verifiable?
- What technological controls are needed for the large-scale testing and deployment of NETs?
- Can we quantify the risks of applying NETs, such as the impacts of some NETs on water and energy availability and food production?
- What legislative and governance frameworks are required to support the development, deployment and uptake of NETs?
- What monitoring and evaluation frameworks are used around the world to understand the effectiveness of various NETs?
- What incentive structures are used around the world to stimulate investment in NETs R&D?
- What incentive and regulatory structures are used around the world to promote the deployment of NETs?
- What are legal and regulatory frameworks in place that may promote/impede NETs development across different domains?
- What is the role (if any) of Public-Private Partnerships (PPP) within the NETs context?

### 3.2.6 Earth System Considerations.

- What is the net size of the contribution of each of the NETs?
- What is the stability and lifetime of sequestered carbon?
- What are the key feedbacks between NETs and the Earth System (e.g. Ocean-Atmosphere feedback)?
- What are the implications of NETs on existing ecosystem services?
- How sensitive or exposed are different NETs to different emissions trajectories or variability? e.g. unforeseen climate/earth system events or extremes?
- Is there an opportunity for additional (unforeseen) environmental co-benefits?
- Can we quantify the risks of applying NETs to the Earth System?

- What are the environmental risks, costs and benefits (including co-benefits) of implementing NETs in the Australian context?

## 3.3 Roadmap for National Capability: Australia's realisable sequestration supply

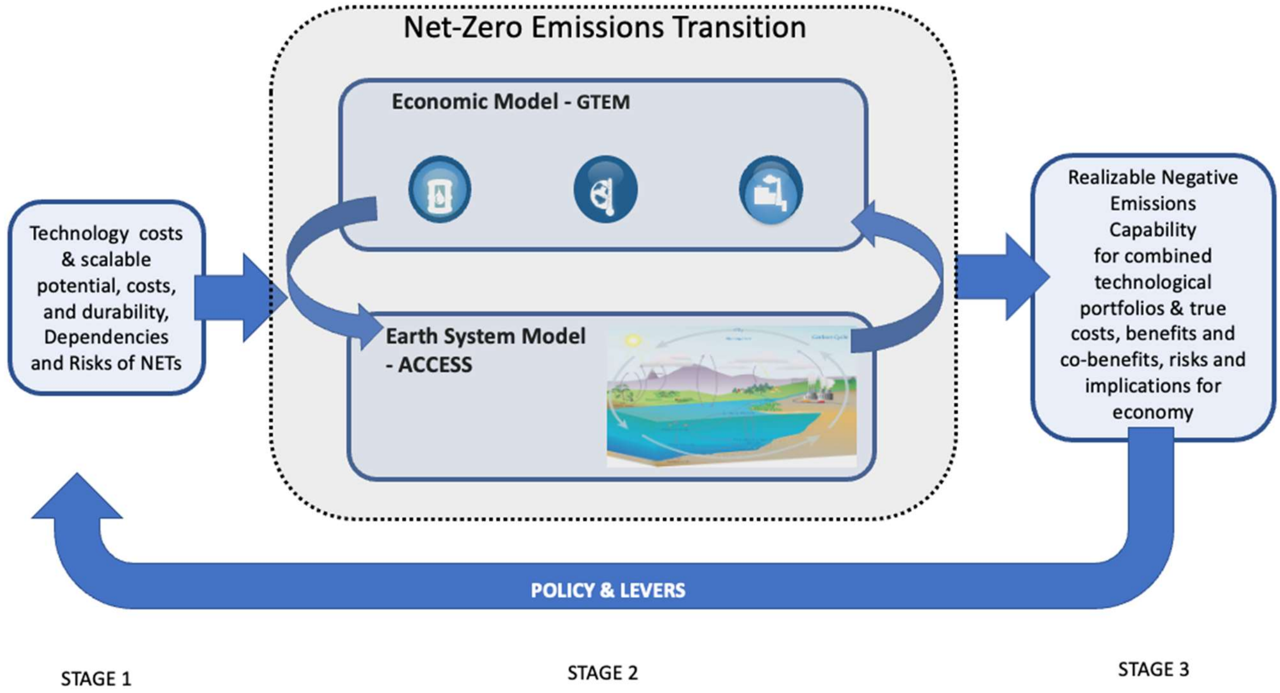



**Figure 3-1: Schematic of national capability for the deployment of NETs and their realisable Negative Emissions**

The first stage of the development toward establishing a national capability refers to the information delivered in this current study and identifying gaps for future work and the work in the proposed (second) stage of this current report. Followed by a deeper dive into individual approaches and address many of the gasps identified in the *Technology Advancement* Section (1.2) . The pillar represents this on the left-hand side of Figure 3.1. This requires regular revisiting at least bi-annually (ideally annually) to ensure new and emerging technologies and innovation breakthroughs are captured.

The second stage is building the Integrated Assessment Modelling (IAM) approach, around state-of-the-art earth system and economic models coupled together in a net zero transition framework (centre-column). This will also involve developing different economic and earth systems representations of NETs to be developed, including using their life-cycle analyses, energy demands, and bio-physical dependencies such as water and land. It also allows risks and potential risks to be identified as implications for the broader economy, such as food systems and prices.

The third stage is developing the portfolio of different NETs to be explored and optimised based on social, earth systems, social and economic challenges, and settings (right-hand column). The arrow linking the third stage to the first stage indicates the policy drivers and other levers that could potentially advance technology development, reduce costs and incentivise the markets.

## 3.4 A path to National Capability: Australia’s realisable sequestration supply

The path to developing and implementing this national capacity will require establishing a steering group responsible for this development made up of representatives from industry, government, universities, and research agencies. This steering group will be responsible for:

- Scoping and costing the national capability development
- Explore different funding models, including potential partnerships
- Developing the timeline of the development of delivery and critical milestones
- Understanding the needs of key stakeholders, including state and federal governments, industry groups, first nations peoples and others that will draw upon the outputs from this national capability
- Forming working groups to undertake the technical development required, such as the representation of new technologies, coordination of critical inputs and computing infrastructure
- Consultation around the delivery of the outputs from the national capability, including visualisation and resolution

The development of national capability will require significant investment likely to be of the order of $3-5M over 18-24 months. Further development would require a modest investment to ensure ongoing model development and improvement, including new technology implementation and changes in national and internal policy settings.

# Technology Reviews

# 4 Permanent Plantings

| **Emission Type** | Avoided | Negative |
|---|---|---|
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Table 4-1: Permanent plantings technology type**

## 4.1 Summary

**Description and current uptake**

Permanent plantings are not-for-harvest plantings of woody vegetation established on land that is currently non-forested, typically on previously cleared agricultural land. The plantings can be located anywhere in the landscape and can range from broad-scale blocks through to narrow belt plantings (such as shelterbelts). Carbon in permanent plantings is sequestered in the living biomass, forest debris and soil.

Within Australia's Emissions Reduction Fund (ERF), there are two eligible methodologies. Plantings under the first methodology can be either a mix of trees, shrubs and understory species native to the local area or a species of mallee eucalypt. Plantings under the second methodology can be any forest tree species other than prescribed weeds.

The practice of planting trees is well established, with several private companies, non-governmental organisations and not-for-profit organisations specialising in establishing and maintaining plantings.

To provide an estimate of current uptake from permanent planting sequestration, results from Australia's National Greenhouse Gas Inventory[5,6] report average annual average sequestration in environmental plantings across Australia, over the period 2010-2020, of 2.1 Mt $CO_2$-e $yr^{-1}$. This estimate includes soil carbon as well as living biomass and forest debris. The Potential and Economic sequestration estimates reported below include only living biomass and debris, based on previous modelling.

**Sequestration potential**

Technical sequestration associated with environmental block plantings is estimated to be approximately 480 Mt $CO_2$-e $yr^{-1}$ (25-year annual average) covering an area of 63.3 Mha. At a carbon price of $30 t $CO_2$-e, the economic sequestration associated with environmental block plantings is 16 Mt $CO_2$-e per year (25-year annual average) for a cost of $20-$30 per tonne. For the subset of the potential area that could be established with narrow belt plantings (shelterbelts), technical sequestration was approximately 36 Mt $CO_2$-e $yr^{-1}$ (25-year annual average) covering an area of 3.1 Mha. At a carbon price of $30 t $CO_2$-e, the economic sequestration associated with environmental block plantings is 0.4 Mt $CO_2$-e per year.

**Technology readiness potential and commercial readiness**

[5] National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

[6] Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

Ecosystem revegetation and reforestation activities are well established in the marketplace. The relative lack of uptake of these methodologies suggests there are existing barriers, particularly the current carbon price (where alternative land uses in higher productivity areas are more profitable than carbon farming).

**Scalability, length of storage, measurement and verification**

There is a large gap between economic potential and technical sequestration associated with this activity, largely driven by economics, where high initial upfront costs are particularly significant, as are the opportunity costs of changing production systems. In addition, permanent plantings require access to suitable land and water resources, and thus compete with other land uses more generally.

Most risks associated with permanent plantings are associated with rates of sequestration (such as reduced tree growth due to persistent increases in temperature and water stress, and disturbance from heat-stress and droughts arising from a changing climate). Young plants are more vulnerable to climatic stresses than more mature plantings. Wildfires and pests and diseases are also risks to the permanence of carbon sequestration.

For permanent plantings, the measurement and verification processes are well developed. Sequestration is readily observable from the ground, aerial imagery and remote sensing, although high resolution (<10m) imagery is required to discern narrow belt plantings.

**Social, environmental impacts, risks and co-benefits**

At present activity levels, there are limited social risks and impacts. Widespread adoption of permanent planting activity could potentially see disruption to traditional farming practices. Large-scale afforestation may also have impacts on catchment water flows, and widespread permanent plantings may be subject to water licensing in catchments that are over-allocated or approaching full allocation.

As a co-benefit to carbon sequestration, biodiversity enhancement associated with mixed-species environmental plantings may be a significant driver of afforestation. Other co-benefits of integrating trees within agricultural landscapes, particularly in shelterbelt and other linear configurations, include the potential to enhance existing farm productivity and profitability (for example, through reducing evaporation from the soil surface, slowing surface water flows and reducing soil erosion).

**Barriers to implementation**

Under current ERF permanent planting methodologies, soil carbon is excluded; however, recent evidence confirms that there is potential to sequester soil organic carbon under permanent plantings. This suggests there is potential to extend current methodologies to include soil carbon. Permanent plantings are widespread within Australia, demonstrating broad acceptance of the technology.

While establishing environmental and mallee plantings offers significant sequestration potential, the economics are limiting. Opportunities for increasing economic viability could include reducing costs associated with project development and registration, financially recognising the agricultural and environmental co-benefits associated with revegetation and developing mechanisms for forward crediting (to buffer early growth years, when sequestration rates are lowest, and establishments costs are high).

Potential industry and supply chain limitations include ensuring adequate source material (either seeds or tubestock) and accessing suitably qualified skills and best-practice establishment methods. Permanent vegetation planting activities are already supported by the ERF and its associated market mechanism. Creating market mechanisms that allow smallholders to participate with limited costs would provide additional opportunities

**Scaling knowledge gaps**

Research is needed to further quantify the social and environmental co-benefits of integrating trees into agricultural landscapes and to identify additional incentives for uptake. Expansion of the analyses should include a broader range of carbon prices and land eligibility beyond those within the constraints of the ERF permanent planting framework.

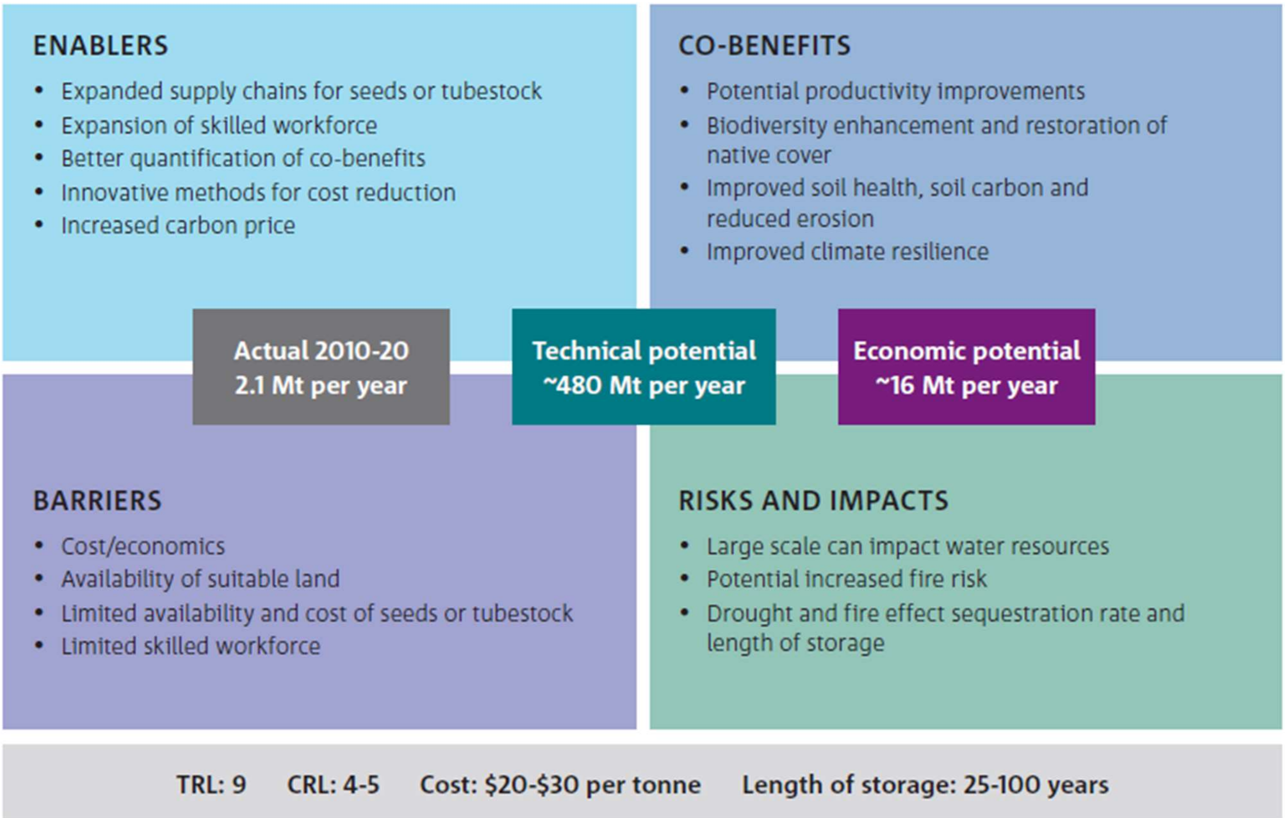



**Figure 4-1: Summary of Permanent Plantings. Actual sequestration reflects sequestration in environmental plantings over the period 2010-2020, as reported in Australia's annual national greenhouse gas inventory. Actual sequestration includes soil carbon as well as living biomass and forest debris, whereas the Potential and Economic potential estimates include only living biomass and debris. Values in parentheses for Potential and Economic potential are the narrow belt/shelterbelt plantings subset.**

**Case study: Shelterbelt tree plantings**

Integrating shelterbelt tree plantings within agricultural landscapes has long been identified as an activity that can deliver multiple benefits to both landholders and the environment, over and above benefits associated with increasing ecosystem carbon storage[7]. These benefits include providing windbreaks to protect crops and livestock from harsh climatic conditions, leading to reduced animal stress and increased productivity. Other benefits include providing habitat for flora and fauna, increasing habitat connectivity across landscapes, reducing windspeed and associated impacts on soil erosion, and improving farm aesthetics and increasing privacy. If the planting comprises commercial plantation species, then this can provide additional economic benefits, through providing alternate income streams from harvested wood products. Although these benefits are well appreciated (as well as potential dis-benefits, such as tree competition with adjacent pasture or crops) the scientific basis for these impacts remains relatively poorly investigated.

This case study highlights an experimental investigation of the impacts of linear (shelterbelt) tree plantings across four sites in northern Tasmania, undertaken by CSIRO, The University of Tasmania, and Private

[7] https://www.climatechangeauthority.gov.au/publications/reaping-rewards-research-report

Forests Tasmania[8]. The aim of the study was to better understand the benefits (and dis-benefits) of integrating commercial plantation trees (*Pinus radiata*) into existing farming systems. The key outcomes of the study were:

- Average wind speeds were 20-50% lower in the lee of the plantings (*Pinus radiata*), compared to unsheltered or open paddock.
- Tree shelter reduced evaporation by 15-20%, meaning increased soil water availability to support pasture growth.
- In the shelter of the planting the pasture produced 30% more biomass than unsheltered or open paddock.
- An economic analysis applied to one of the case study farms (a square paddock of approximately 25ha) showed gross returns from the tree planting over 25 years of approximately $54k, comprising tree harvest ($14k), shelter benefits to productivity ($42k), carbon sequestration ($3k) and amenity/land value ($1k). Net costs, including fencing, were approximately $6k.

Taken together, this case study demonstrated the integration of shelterbelt plantings into existing farming systems increased farm profitability, reduced vulnerability to weather extremes, diversified farm incomes, and provided climate change mitigation benefits through increased farm carbon storage. The study showed the integration of trees into farming systems can bring benefits several-fold the value of the trees, and that small areas of trees can make a disproportionate impact on overall returns and environmental impacts.

**Photo: Shelterbelt established adjacent to grazing paddock, protecting livestock from wind. Photo credit: Arthur Lyons**.

## 4.2 Description and current uptake

Permanent plantings are not-for-harvest plantings of vegetation that are established on land that is currently non-forested, typically on previously cleared agricultural land. Their location might be anywhere in the landscape and can range from broad-scale block plantings that could cover several 10s or 100s of hectares to narrow belt plantings or shelterbelts. Carbon under permanent plantings is sequestered in the living biomass, in the forest debris, and in the soil (England et al. 2016; Paul et al. 2018). When established with locally endemic native species, permanent carbon plantings can provide a mechanism for ecosystem restoration, and more generally, permanent plantings offer many co-benefits associated with habitat connectivity and biodiversity, among others.

Results reported in Roxburgh et. al. (2020a) were used to provide estimates of future sequestration associated with permanent plantings across the Australian continent. Although the analyses in that report

[8] https://www.treealliance.com.au/__data/assets/pdf_file/0015/255300/CSIRO_Report_-_Modelled_costs_and_benefits_of_agroforestry_systems.pdf

were specific to sequestration that could be achieved under current relevant ERF methodologies, they can be considered broadly representative of the sequestration that could be achieved by permanent plantings more generally. This was ensured through (a) estimating technical sequestration based on block environmental plantings, which in the analysis were minimally constrained by ERF methodology-specific limitations (and which also embed (spatially) other eligible planting types, such as mallee plantings and belt plantings); and (b) calculating economic sequestration as the financially viable subset of technical sequestration, with carbon price used as a proxy to represent constraints such as the financial costs of establishing plantings on farms, inclusive of current land production. Consistent with the ERF methodologies, soil carbon was not included in the analyses.

Within Australia's ERF, the sequestration of carbon in permanent plantings involves the establishment of mixed-species environmental or single-species plantings. Analyses based on these ERF methods are used to inform the sequestration estimates in this section (Roxburgh et al. 2020a). There are currently two eligible ERF methodologies, *Reforestation by Environmental or Mallee Plantings – FullCAM* (2014), and *Reforestation and Afforestation (2.0)* (2015). Under the *Reforestation by Environmental or Mallee Plantings* methodology plantings can be either a mix of trees, shrubs and understory species native to the local area, or species of mallee eucalypts. Under the *Reforestation and Afforestation* methodology, any forest tree species other than prescribed weeds are eligible. Through establishing woody vegetation on currently non-forested land, $CO_2$ is sequestered from the atmosphere and stored in the biosphere as plant tissues, forest debris, and soil carbon, although only carbon in plant tissues and forest debris is currently recognised under each of the ERF methods.

The practice of planting trees is well established, with several private companies, NGOs and not-for-profit organisations specialising in establishing and maintaining plantings through time. The environmental benefits associated with restoration and revegetation are significant, with carbon being only one of many co-benefits, with other additional benefits such as habitat restoration and enhancing biodiversity, soil stabilisation, and managing surface runoff. Both the measurement and modelling of carbon accumulation in plantings are also well established.

Estimates of current rates of sequestration for environmental plantings obtained from Australia's National Greenhouse Gas Inventory[9,10], averaged over the period 2010-2020, are 2.1 Mt $CO_2$-e $yr^{-1}$. Note this value includes living biomass, debris and soil carbon, whereas the estimates of potential and economic sequestration reported below exclude soil carbon.

9 National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

10 Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

## 4.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt.yr $^{-1}$) | Key evidence |
|---|---|---|
| **Technical Potential**[1] | 478.3<br>(36.2) | Based on spatial modelling to identify potential areas for future activity, and FullCAM simulations to calculate sequestration potential (Roxburgh et al. 2020a). |
| **Economic potential by 2025** | NA | |
| **Economic potential by 2035** | NA | |
| **Economic potential by 2050** | 16.0<br>(0.4) | Based on discounted cash flow modelling of the technical sequestration results, with an assumed carbon price of $30 t CO2-e, and a discount rate of 10% (Roxburgh et al. 2020a). |

[1]The technical sequestration area excludes land occupied by current ERF projects undertaking permanent planting projects. Only results from the block planting analyses are shown, as the potential land area for belt plantings is a smaller subset of that for blocks.
[2]The economic sequestration calculation did not consider the possible time course of delivery, nor the staggering of new projects over time, hence no time course of ACCU delivery is provided. The economic sequestration value represents the maximum sequestration achievable assuming all new potential projects could be established over the near term (e.g., the next 1-2 years).

**Table 4-2: Best estimate of Permanent Plantings sequestration potential. Values in parentheses are the subset of the total estimate associated with narrow belt/shelterbelt plantings.**

### 4.3.1 Technical sequestration

Technical sequestration is based on predictions of forest carbon sequestration from the FullCAM model (Full Carbon Accounting Model). Consistent with the ERF methodologies the sequestration estimate includes all above-ground and below ground living biomass and debris but excludes soil carbon. Operationally, for any project that is affected by fire (either planned fire or wildfire) rules specify how the modelling must be modified to account for any fire emissions incurred, and any re-stratification of the project extent that might be required in case of significant fire-induced tree mortality. Other project-specific adjustments to the modelling include the need to include fossil fuel usage and other emissions associated with project establishment and maintenance, and maintenance events such as thinning. The implications of these adjustments were assumed negligible and were not included in the modelling (e.g., fossil fuel usage is typically a very small fraction of total sequestration, and at the continental scales fire impacts were assumed small relative to the total rates of sequestration).

To provide a comprehensive library of model results on which to base further analyses, independent of any ERF-specific constraints, FullCAM spatial growth predictions of combined above- and below ground living biomass and forest debris were saved annually from planting year 0 (with biomass and debris carbon stocks assumed to be 0.0) to year 30, and at year 100. The growth model calibrations used in the simulations were for native forest regeneration on lands managed for environmental services ($Block_{ES}$), and low and high planting density belts, for both environmental plantings and Mallee species (Paul and Roxburgh 2020). For all analyses, historical average climatic conditions were assumed.

Whilst the FullCAM model outputs provide a comprehensive 'wall-to wall' continental-scale library of forest regeneration potential, for assessing the scope of potential future activity it was necessary to mask out those areas that are either biophysically unsuitable or otherwise unlikely to support the successful establishment of new vegetation. This was achieved by progressively applying a set of five spatial filters.

1. *Inclusion based on current land use*

   The first filter includes only land that is classified as either grazed modified pastures, dryland cropping, irrigated pastures, or irrigated cropping, based on the Land Use of Australia 2010-2011 coverage (ABARES 2017).

2. *Exclusion based on current forest cover*

   Planting projects under the ERF methodologies are only eligible on land that has been for the previous 5 years non-forested/non-sparse but has the potential to attain forest cover. Therefore, areas of land that are currently forested or sparse vegetation were excluded from the analysis. The National Forest and Sparse-Woody Vegetation Data version 3 (DoEE 2018a) was used to identify areas that have been cleared over the previous five years. This dataset is provided at a high spatial resolution (approximately 25 m x 25 m continentally), and for data manageability was re-sampled to 250 m x 250 m, recording the total number of non-forested/sparse 25 m x 25 m grid cells within each target 250 m x 250 m grid cell.

3. *Inclusion based on potential to support forest cover*

   To differentiate land that is currently naturally non-forest (such as grasslands and shrublands), from land that is currently non-forest but has the potential to attain forest cover, the National Vegetation Inventory System (NVIS) pre-1750 classification was used (DoEE 2018b). Only land that was mapped as potentially able to support forest cover was included.

4. *Exclusion of current ERF projects*

   Current ERF project areas were excluded from the analysis, on the basis they are either currently forested, or will attain forest cover in the immediate future, and hence unavailable to establish new plantings.

5. *Exclusion of rainfall areas greater than 600 mm*

   Land in the project area on which a mallee planting occurs must receive long-term average rainfall of 600 millimetres or less. Areas greater than 600 millimetres rainfall were excluded for Mallee plantings.

Intersecting constraints 1-5 yielded a total potential area for future plantings of 63.3 Mha, and a total potential area for future Mallee plantings of 41.9 Mha (Figure 4-2).

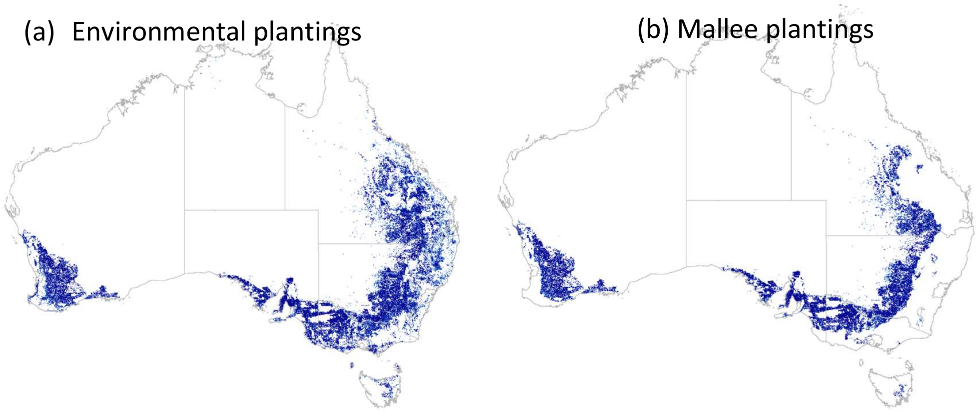



**Figure 4-2: (a) Potential extent of possible future environmental planting activity; (b) potential extent of possible future mallee planting activity**

Intersecting the areas in Figure 4-3 with the FullCAM modelling gives the technical sequestration estimates in Table 4-2. Because narrow belt plantings are, by definition, confined to small areas such as shelterbelt plantings along the edges of paddocks, the technical sequestration for these plantings was limited to 5% of that of the broader landscape. This assumes that most land managers would keep a majority of their farm under agricultural production, with 5% providing a conservative estimate of potential reforestation activity that would minimally impact farm productivity (Paul et al. 2016).

| Planting type | 25yr sequestration (Mt CO2 e) | 25yr annual average (Mt CO2 e yr $^{1}$) | Area (MHa) |
|---|---|---|---|
| **EP Block Environmental Services** | 11958.57 | 478.34 | 63.3 |
| **EP Belt Low stocking** | 829.80 | 33.19 | 3.1 |
| **EP Belt High stocking** | 904.52 | 36.18 | 3.1 |
| **Mallee Block Environmental Services** | 8286.19 | 331.45 | 41.9 |
| **Mallee Belt Low stocking** | 574.96 | 23.00 | 2.1 |
| **Mallee Belt High stocking** | 626.13 | 25.04 | 2.1 |

**Table 4-3:** Technical sequestration associated with the environmental and mallee plantings for the areas identified in **Figure 4-2**.

The level of confidence in the overall sequestration estimates is medium. The FullCAM model is well calibrated for environmental and mallee plantings and hence the confidence in the overall sequestration quanta is high, although the level of confidence in the spatial extent, including the 5% assumption for belt plantings is medium, hence the overall rating of medium. The level of confidence in pixel-level sequestration estimates is low. The technical sequestration reported here is within the range of previous estimates, reviewed by Roxburgh et al. (2020a) (143 - 513 Mt CO2-e yr$^{-1}$).

### 4.3.2 Economic sequestration

It is important to differentiate between the area of land that is assessed as potentially being able to support new plantings, and that is realistically available and that could be planted – the economic sequestration subset. Consistent with prior work (Eady et al. 2009) a financial filter was applied to limit the technical sequestration areas to the Economic potential subset. Economic viability was based on both the direct and the opportunity costs of undertaking activities, compared against the expected revenues.

Discounted cash flow modelling was applied, whereby locations were flagged as being likely to transition to carbon farming if the net present value (NPV) of the carbon farming activity exceeded current profitability, with an assumed discount rate of 10%. Full details of the economic modelling are provided in Roxburgh et al. (2020a). Because the economic sequestration is sensitive to the assumed carbon price, minimum and maximum values are presented, corresponding to carbon prices of $15 t CO2-e and $30 t CO2-e, respectively.

The Reforestation and Afforestation methodology is based on field measurement, and hence the economics differ slightly from that of the Reforestation by Environmental or Mallee Plantings – FullCAM methodology, where sequestration is based on FullCAM modelling. The feasibility results for both methods indicate only minor differences in the overall outcomes (), as the field measurements for the Reforestation and Afforestation methodology were based on the same FullCAM modelling as used in the Reforestation by Environmental or Mallee Plantings – FullCAM methodology, and the additional costs of measurement were not significant relative to the sequestration rates achieved.

Note that no consideration was given in the analysis to additional factors that could limit future uptake of natural regeneration of permanent planting activities, such as technological barriers (Rooney & Paul 2017). Note also that the values in Table 4-3 also represent maximum economic potentials, as they do not take into account the staggered introduction of new projects over time; rather, the values represent the economic sequestration that could be achieved if all possible new projects could be established over the short term (1-2 years). Slightly less sequestration is predicted under the *Reforestation and Afforestation* analysis due to increased costs associated with the field measurement requirements of this method.

The spatial extent of the EP Block services sequestration estimates includes as a subset sequestration from all the other categories in Table 4-3. Although sequestration between belt and block plantings is not directly substitutable, as on a per ha basis belt plantings sequester carbon at a faster rate compared to block plantings (Paul et al. 2014a,b), for the purposes of this report, the EP Block Environmental Services value for the $30 t $CO_2$-e price scenario under the *Reforestation and Afforestation* methodology is used as the basis for the summary, to provide un upper limit to the potential (16.043 Mt $CO_2$-e $yr^{-1}$). Because of the potential for narrow belt plantings to be integrated into existing farming systems (see case study), sequestration for the environmental planting belt high stocking subset is also shown as a separate line item in the summary Table 4.1.

| Planting type | 25yr sequestration ($Mt\ CO_2\ e$) | 25yr annual average ($Mt\ CO_2\ e\ yr^{1}$) | Area (MHa) |
|---|---|---|---|
| ***Reforestation by Environmental or Mallee Plantings – FullCAM*** | | | |
| **EP Block Environmental Services** | 38.057 – 401.069 | 1.522 - 16.043 | 0.029 - 0.563 |
| **EP Belt Low stocking** | 2.197 – 27.908 | 0.088 – 1.116 | 0.001 - 0.026 |
| **EP Belt High stocking** | 0.856 – 10.439 | 0.034 - 0.418 | <0.001 - 0.007 |
| **Mallee Block Environmental Services** | 1.091 - 55.02 | 0.044 - 2.201 | 0.001 - 0.062 |
| **Mallee Belt Low stocking** | 0.181 – 5.731 | 0.007 - 0.229 | <0.001 - 0.005 |
| **Mallee Belt High stocking** | 0.000 – 1.435 | 0.000 - 0.057 | 0.000 - 0.001 |
| ***Reforestation and Afforestation*** | | | |
| **EP Block Environmental Services** | 34.357 – 363.280 | 1.374 - 14.531 | 0.026 - 0.498 |
| **EP Belt Low stocking** | 1.232 - 13.543 | 0.049 - 0.542 | 0.001 - 0.010 |
| **EP Belt High stocking** | 0.293 – 6.157 | 0.012 - 0.246 | <0.001 - 0.004 |
| **Mallee Block Environmental Services** | 1.015 – 51.149 | 0.041 – 2.046 | 0.001 - 0.057 |

| | | | |
|---|---|---|---|
| **Mallee Belt Low stocking** | 0.067 – 3.226 | 0.003 - 0.645 | <0.001 - 0.002 |
| **Mallee Belt High stocking** | 0.000 - 0.627 | 0.000 - 0.025 | 0.000 - <0.001 |

**Table 4-4: Economic sequestration associated with environmental and mallee plantings for the areas identified in** Error! Reference source not found.**, for each of the *Reforestation and Afforestation* and *Reforestation by Environmental or Mallee Plantings – FullCAM* methodologies. The ranges reflect two carbon price assumptions, $15 t $CO_2$-e (lower bound) and $30 t $CO_2$-e (upper bound).**

## 4.4 Technology Readiness Potential and Commercial Readiness

### 4.4.1 Technology Readiness

| Technology Readiness | $ per tonne $CO_2$e | Key Evidence |
|---|---|---|
| 9 | ~20-30 | Only direct costs of undertaking activities are included in the price, comprising project transactions costs (assumed to be 25% of achieved sequestration), annual maintenance ($103 $ha^{-1}$), fencing for belt plantings ($4 $m^{-1}$), and establishment costs ($2580 $ha^{-1}$). |

**Table 4-5: Technology readiness assessment for permanent plantings**

**Explanation:**

Ecosystem revegetation and reforestation activities are well established in the marketplace.

### 4.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| **4-5** | The current projects that have received ERF contracts demonstrate that the technology is commercially ready. Although reforestation is reasonably widespread across temperate Australia (also extending into subtropical Australia), the analyses above suggest a significant untapped potential, both within and outside of the ERF. This suggests additional incentives over-and above carbon payments may be required to further increase uptake. |

**Table 4-6: Commercial readiness assessment for permanent plantings**

**Explanation:**

Whilst the technology is well developed, the relative lack of uptake suggests a number of existing barriers, particularly the current carbon price where many marginal productivity areas are still uneconomic; and where alternative land uses in the higher productivity areas are significantly more profitable than carbon farming. Recognition of associated co-benefits, such as biodiversity outcomes, provides an opportunity to improve the commercial readiness of this activity (see 4.6.3 below).

## 4.5 Scalability, Length of storage, Measurement and Verification

### 4.5.1 Scalability.

There is a large gap between economic potential and technical sequestration associated with this activity, largely driven by economics, where high initial upfront costs are particularly significant, as are the opportunity costs of changing production systems (Rooney and Paul 2017). An additional limitation is that tree planting in agricultural landscapes involves a trade-off between land used for producing food, and land used for carbon farming. The potential land area identified above includes all available agricultural land. Only a small proportion of this would ever be converted into tree plantings, given the ongoing need to feed human populations.

### 4.5.2 Length of storage

Assuming successful establishment and ongoing natural regeneration then the length of carbon storage in permanent plantings is indefinite (> 100 years). Most risks associated with permanent plantings are associated with rates of sequestration, arising from reductions in tree growth from persistent increases in temperature, persistent increases in water stress, and heat-stress and droughts arising from a changing climate. The greatest risk period is soon after planting or germination, when plants are young and more vulnerable to climatic stress. Wildfires are also a particular risk factor, associated with risks to permanence, as are the impacts of pests and diseases. Adaptation options include varying planting species and genetic stock, altering planting configuration to reduce risks of resource limitations, careful site preparation and timing of establishment, and fire risk reduction management. Selective breeding for genotypes that confer increased resilience to climate extremes is also a response option. Many of the adaptive measures are currently applied in the context of plantation forestry but could also be modified for permanent plantings (Roxburgh et al. 2020b).

### 4.5.3 Measurement and Verification

Integrity of the sequestration is high, with measurement and verification processes well developed, and the sequestration readily observable from the ground, and from aerial imagery and remote sensing, although high resolution (<10m) imagery is required to discern narrow belt plantings.

## 4.6 Social, environmental impacts, risks and co-benefits

### 4.6.1 Social impacts and risks

At present levels of activity there are limited social risks and impacts. Widespread future adoption of permanent planting carbon farming activity could potentially see disruption to traditional farming practices, however the ongoing need to retain productive agricultural land and the unfavourable economics of establishing carbon plantings on productive agricultural land would suggest this risk is low.

Belt or other widely spaced plantings, designed to be integrated with (and to enhance) current production systems, provides a risk mitigation mechanism to facilitate carbon farming to be embedded within existing agricultural landscapes (see case study).

### 4.6.2 Environmental impacts and risks

Large-scale afforestation may also have impacts on catchment water flows, and widespread activity may be subject to water licensing in catchments that are over-allocated or approaching full allocation. The potential for increased fuel loads across the landscape to increase fire risk has been raised, with one study indicating elevated wildfire risk, although only under extreme fire danger conditions (Jenkins et al. 2016).

### 4.6.3 Co-benefits

Biodiversity benefits are often associated with revegetation by mixed-species environmental plantings, with monocultures and non-endemic mixtures of species often considered to be of lower (though not necessarily negligible) biodiversity value (Paul et al. 2016). Biodiversity can be measured across different scales of time and space, and the beneficial impacts can be localised or regional. They can also be specific to some species, or they can provide general restoration of habitat. Biodiversity enhancement may therefore be a significant driver of afforestation, as a co-benefit to carbon sequestration. Other co-benefits of integrating trees within agricultural landscapes, particularly in shelterbelt and other linear configurations, include the potential to enhance existing farm productivity, and profitability. For example, through reducing wind speed (that reduces evaporation from the soil surface, and provides protection for sheltering stock), slowing surface water flows, localised salinity management, and reducing soil erosion.

## 4.7 Barriers to implementation:

### 4.7.1 Policy and regulatory environment

Current ERF permanent planting methodologies exclude soil carbon. With recent evidence confirming the potential to sequester soil organic carbon under permanent plantings (England et al. 2016; Paul et al. 2018), this suggests the potential to extend or 'stack' current ERF methodologies to include soil carbon, leading to increased sequestration and improved profitability.

### 4.7.2 Social licence and stakeholder acceptance

Widespread (albeit scattered) permanent planting activity within Australia suggests broad-scale acceptance of the activity. The reasons for the limited uptake of permanent planting activity relative to the potential are unclear, but likely involve both economic and social considerations. Based on a series of landholder interviews, Fleming et al. (2019) concluded that limited uptake of tree planting activity on farms is at least partly due to the current framing of carbon farming benefits solely on financial considerations, and that broader identification and communication of associated economic, environmental and social co-benefits has the potential to re-invigorate how carbon farming is perceived and adopted.

### 4.7.3 Technology performance variability

Carbon outcomes from planting trees is inherently variable, both across space (due to variation in soil type, landscape position, etc.) and time (due to climatic variability, disturbances such as fire, etc.). As such this adds an element of risk to the activity.

### 4.7.4 Financial proposition and costs and access to capital

Overall, the establishment of environmental and mallee plantings offers significant sequestration potential, however the economics of the activity are such that only a small fraction of that potential is likely to be realised. Opportunities for increasing the economic viability of these activities could be explored to help increase uptake. These could include generic solutions such as reducing costs associated with project development and registration, financial recognition of the agricultural and environmental co-benefits associated with revegetation, and mechanisms for forward crediting to improve the economic viability during the early years of projects when sequestration rates are the lowest.

### 4.7.5 Industry supply chains and skills

Potential limitations to rapid expansion of permanent plantings includes ensuring adequate source material (either seeds, or tubestock plantings) to facilitate widespread uptake, and access to suitably qualified skills to ensure successful site preparation, appropriate selection of species, and best-practice establishment methods.

### 4.7.6 Market opportunities or market creation

Permanent vegetation planting activities are already supported by the ERF and its associated market mechanism, with ACCUs purchased either directly by government, or traded on the open market. However, given relatively low uptake under the ERF, and the fact that shelterbelt and other integrative tree farming practices are applicable only to a small fraction of productive farm systems, creating market mechanisms that allow smallholders to participate with limited costs would provide additional opportunities. This could include stacking of activities under a single method, and extension of allowable activities and/or carbon pools, for example the inclusion of include soil carbon.

## 4.8 Scaling knowledge gaps:

The science underpinning growing trees for carbon sequestration is well established, and well understood. Additional research areas receiving current attention are alternative planting techniques that reduce other on-farm impacts, such as wide-spaced plantings within paddocks to still allow grazing access. Further research questions include:

- What are the additional investments that could increase uptake by targeting a better quantification of the social and environmental co-benefits of integrating trees into agricultural landscapes?
- How does a broader range of carbon prices and land eligibility scenarios effect the estimates of sequestration?
- What is the impact on uptake if soil carbon is included the analyses?

## 4.9 Chapter References


ABARES. (2017) Land use of Australia 2010-11. https://data.gov.au/dataset/ds-dga-bba36c52-d5cc-4bd4-ac47-f37693a001f6/details.

DoEE. (2018a) National Forest and Sparse-Woody Vegetation Data (Version 3, 2018 Release). Department of Environment and Energy, Commonwealth of Australia, Canberra

DoEE. (2018b) NVIS Major Vegetation Subgroups (Version 5.1). Department of Environment and Energy, Commonwealth of Australia, Canberra

Eady, S. et al. (2009) *An Analysis of Greenhouse gas Mitigation Opportunities from Rural Land Use*. CSIRO.

England, J.R., Paul, K.I., Cunningham, S.C. et al. (2016). Previous land use and climate influence differences in soil organic carbon following reforestation of agricultural land with mixed-species plantings. Agriculture, Ecosystems and Environment, 227, 61-72.

Fleming A., Stitzlein C., Jakku E. & Fielke S. (2019) Missed opportunity? Framing actions around co-benefits for carbon mitigation in Australian agriculture. Land Use Policy 85, 230-8.

Jenkins M., Collins L., Price O., Penman T., Zylstra P., Horsey B. & Bradstock R. (2016) Environmental values and fire hazard of eucalypt plantings. Ecosphere 7, e01528.

Paul, K.I., Roxburgh, S.H., England, J.R. et al. (2014a). Improved models for estimating temporal changes in carbon sequestration in above-ground biomass of mixed-species environmental plantings. Forest Ecology and Management

Paul, K.I., Roxburgh, S.H., de Ligt, R., et al., (2014b). Estimating temporal changes in carbon sequestration in plantings of mallee eucalypts: modelling improvements. For. Ecol. Manage. 335, 166–175.

Paul K. I., Cunningham S., England J., Roxburgh S. H., Preece N., Brooksbank K., Crawford D. & Polglase P. (2016) Managing reforestation to sequester carbon, increase biodiversity potential and minimize loss of agricultural land. Land Use Policy 51, 135-49.

Paul, K.I., England, J., Baker, T., et al. (2018). Using measured stocks of biomass and litter carbon to constrain modelled estimates of sequestration of soil organic carbon under contrasting mixed-species environmental plantings. Science of the Total Environment, 615, 48-359.

Paul K. I. & Roxburgh S. H. (2020) Predicting carbon sequestration of woody biomass following land restoration. *Forest Ecology and Management* **460**, 117838.

Rooney, M & Paul, K (2017). Assessing policy and carbon price settings for incentivising reforestation and regrowth activities in a carbon market: An Australian perspective. Land Use Policy 67, 725-732.

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020a) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, 389pp.

Roxburgh Stephen H., Paul K. & Pinkard E. (2020b) Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF). Report for the Climate Change Authority.   p. 224.

# 5 Plantation and Farm Forestry

| | | |
|---|---|---|
| **Emission Type** | Avoided | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Table 5-1: Plantation and farm forestry technology type**

## 5.1 Summary

**Description and current uptake**

Plantation and farm forestry technologies increase carbon sequestration by establishing new (for-harvest) plantations on previously cleared land and by changing management practices in existing plantations. These activities sequester carbon in living biomass, forest debris and harvested wood products. At present, it is unclear how the activities impact soil carbon.

Australia's Emissions Reduction Fund has methodologies for commercial plantations and farm forestry. Activities used in the analyses here include establishing new for-harvest forests, and converting existing short rotation plantation forests to long-rotation plantation forests.

Plantation forestry projects are mainly restricted to existing National Plantation Inventory (NPI) regions. New farm forestry projects establish a harvest plantation (or a permanent tree planting) on land that is currently non-forest and that has mostly been used for grazing or cropping for the previous 5 years. These projects are not restricted regionally but under the ERF do have a size constraint (maximum percentage of property extent or maximum number of ha), depending on average annual rainfall.

To provide an estimate of current uptake from plantation forest sequestration, results from Australia's National Greenhouse Gas Inventory[11,12] report give annual sequestration across Australia's plantation forestry estate of 11.5 Mt $CO_2$-e $yr^{-1}$, averaged over the period 2010-2020. This estimate includes soil carbon as well as living biomass and forest debris but excludes harvested wood products; whereas the Potential and Economic sequestration estimates include only living biomass and debris but include harvested wood products.

**Sequestration potential**

Technical sequestration for plantation forestry and farm forestry activities are not spatially independent, given the overlapping land areas on which these activities can take place. This means the separate estimates for plantation forestry and farm forestry cannot be summed to provide a total sequestration estimate. Technical sequestration for plantation forestry was estimated at greater than 630 Mt carbon dioxide equivalents ($CO_2$-e) per year. At a carbon price of $30 t $CO_2$-e, the economic sequestration was

[11] National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

[12] Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

estimated at over 31.8 Mt $CO_2$-e per year, at a cost of \$10-\$30 per tonne. Because it was assumed farm forestry would only occur on a small fraction of existing available agricultural land (5%), and because of the project size limitations imposed by the ERF methodology on which the farm forestry analysis was based, the potential and economic sequestration estimates are lower than for plantation forestry. Technical sequestration for farm forestry was approximately 42 Mt $CO_2$-e per year. At a carbon price of \$30 t $CO_2$-e, the economic sequestration was estimated at 0.63 Mt $CO_2$-e per year. Re-analysis of the farm forestry scenarios, with relaxation of the current project size limitations, would provide a more realistic assessment to total sequestration potential under this activity, and would increase both the potential and economic potential estimates presented here.

**Technology readiness potential and commercial readiness**

Technologies for managing tree plantations are well established. The relatively low uptake of the technology for carbon sequestration suggests other barriers, particularly current carbon pricing and the cost of securing land for forestry in areas with high agricultural productivity. As a carbon sequestration technology, integrating plantations into existing agricultural enterprises would seem to offer significant potential, especially if some of the constraining features of existing ERF methodologies are relaxed.

**Scalability, length of storage, measurement and verification**

The large gap between potential and economic sequestration associated with this technology is partly driven by external factors (such as carbon pricing) and partly by economics (such as high initial and opportunity costs). An additional limitation to scaling is that tree planting in agricultural landscapes involves a trade-off between using land for producing food or for farming carbon in a competition for land and water resources.

Risks to sequestration permanence come from reductions in tree growth due to persistent increases in temperature and water stress, disturbances from heat-stress and droughts arising from a changing climate, wildfires, and pests and diseases.

Measurement and verification processes for plantation and farm forestry technologies are well developed, and sequestration is readily observable from ground-based monitoring, aerial imagery, and remote sensing.

**Social, environmental impacts, risks and co-benefits**

Competition for land use can have a social impact, particularly in areas of high productivity. Although plantation forestry has been shown to provide biodiversity and habitat benefits, adverse environmental outcomes are also possible (such as the spread of exotic species beyond plantation boundaries). Growing forests may also reduce water yield due to increased transpiration, and this may have detrimental impacts on catchment hydrology.

In addition to carbon sequestration, plantation forests can increase landscape connectivity and vegetation complexity and help ameliorate salinity. There are also clear economic and social co-benefits from promoting a regionally based, viable and expanding plantation industry.

**Barriers to implementation**

Strict policies and regulations apply to the establishment of new extensive forests in most parts of Australia, and this can place a regulatory burden on projects. The long history of plantation forestry in many regions has led to broad social acceptance in these areas. However, expansion of plantation forests into new regions may receive a varied response, particularly regarding land use change.

Carbon outcomes from planting trees are inherently variable, affected by variation in soil type or landscape position, by climatic variability or by disturbances such as fire. At the same time, the major barriers to implementation are likely to be economic (such as non-performance of existing plantations, transport costs for wood products, and the price and availability of suitable land).

A key limitation for establishing forest plantations is access to timber processing facilities. Skills in establishing and maintaining for-harvest forests may not be present outside traditional plantation areas; however, this is also a market opportunity. Developing novel uses for wood-based products (such as bioenergy, biochar and aromatic oils) presents additional market opportunities.

**Scaling knowledge gaps**

Improved understanding of plantation and farm forestry activities as sequestration technologies requires including a broader range of carbon prices, land eligibility and activities (such as those associated with new market development). As ERF methodologies for plantation and farm forestry are revised, future analyses need to ensure that they are representative of current and potential activities.

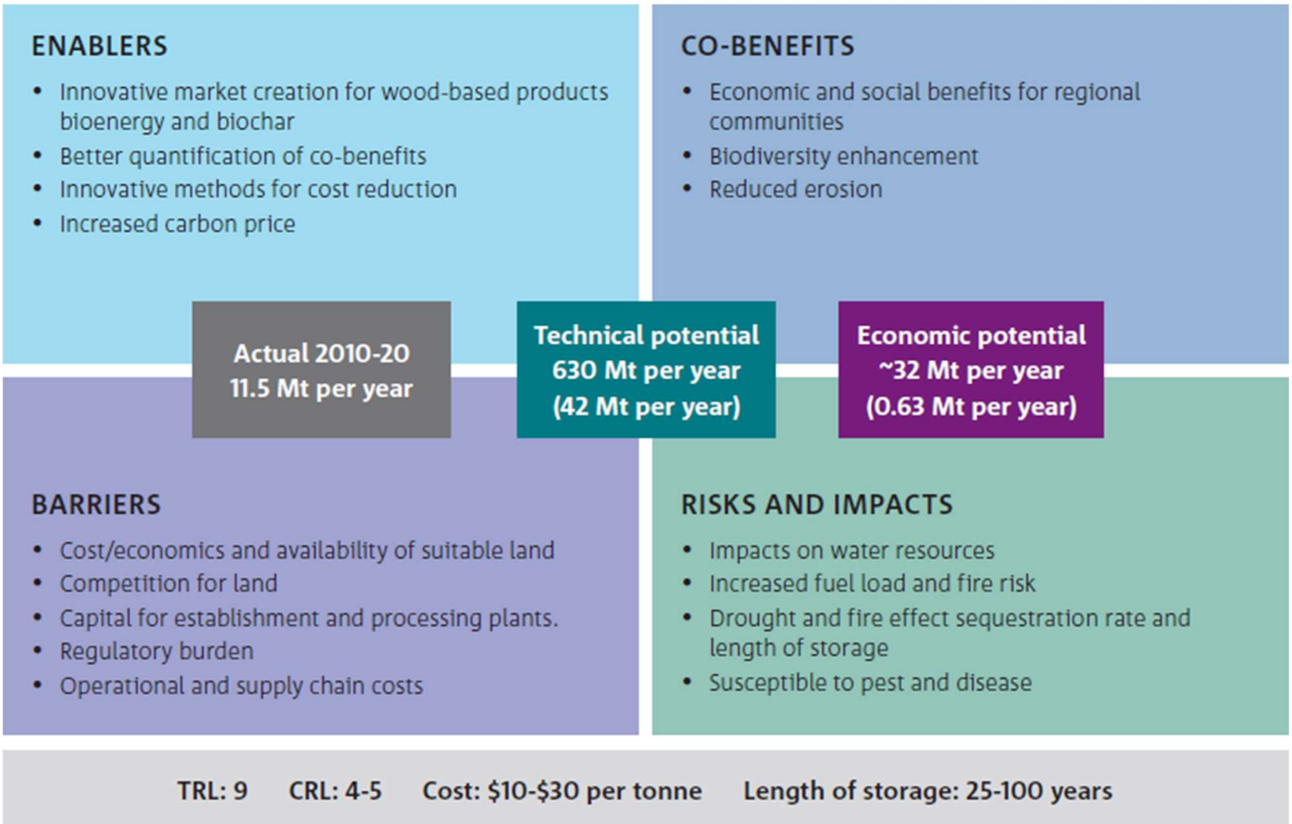



**Figure 5-1: Summary of Plantation and Farm forestry (in parentheses) sequestration. Actual sequestration reflects sequestration in Australia's plantation estate over the period 2010-2020, as reported in Australia annual national greenhouse gas inventory, but excludes farm forestry activity. Actual sequestration includes soil carbon as well as living biomass and forest debris but excludes harvested wood products. The Potential and Economic potential estimates include only living biomass and debris but include harvested wood products.**

## 5.2 Description and current uptake

Plantation forest management and farm forestry increase carbon sequestration through the establishment of new (for-harvest) plantation forests on previously cleared land, and through increasing sequestration in existing plantation estates through management changes such as converting short rotation plantation forests to long-rotation plantation forests, and through retaining forest cover in existing plantations that would otherwise be permanently cleared for agriculture. Carbon under plantation and farm forestry activities is sequestered in the living biomass, in the forest debris, and in the harvested wood products. Changes in soil carbon are, however, less clear-cut, with declines in soil carbon following plantation establishment reported following conversion from both existing native forest (Turner and Lambert 2000) and pasture (Guo and Gifford 2002), most likely due to soil preparation involving mechanical disturbance leading to increased decomposition (Turner and Lambert 2000). Further research is required to identify where, and under what conditions, soil carbon can increase in response to the establishment of new plantations forests.

Analyses based on sequestration in living biomass, forest debris and harvested wood products are used to inform the sequestration estimates in this section (Roxburgh et al. 2020a). These analyses are constrained by the ERF framework within which they were conducted, and were completed prior to the recently revised ERF plantation methodology (*Plantation Forestry* (2022)), which includes additional eligible activities that recognise the carbon benefits from avoiding permanent loss of plantation forests that are intended to be converted back to agricultural land, either through continuation of existing forest management, or replacement of the commercial forest by a not-for-harvest permanent planting. Because these are relatively new activities, no detailed analyses on likely continental-scale sequestration rates or utilisation of these options have yet been undertaken, and hence they are not considered further here. The activities included in this section therefore include the establishment of new for-harvest forests, and the conversion of existing short rotation forests to long-rotation forests. The analyses were conducted with specific reference to, and constraints imposed by, two ERF methodologies: *Plantation Forestry* (2017), and *Measurement Based Methods for New Farm Forestry Plantations* (2014).

Projects under the *Plantation Forestry* methodology are predominantly restricted to the existing National Plantation Inventory (NPI) regions (Figure 5-2), although there are some circumstances where new projects can extend into adjacent non-NPI areas. In contrast, the *Measurement Based Methods for New Farm Forestry Plantations* (2014) methodology involves the establishment a harvest plantation (or a permanent planting of trees) on land that is currently non-forest, and that has predominantly been used for grazing or cropping for the previous five years; farm forestry projects are thus not restricted regionally. However, under the ERF Farm Forestry methodology, farm forestry projects do have a project size constraint. In areas of average annual rainfall more than 400mm the maximum project size is the lesser of 100ha, or 30% of the property extent. In areas of average annual rainfall less than 400mm the maximum project size is the lesser of 300ha, or 30% of the property extent.

To provide an estimate of current uptake from plantation forest sequestration, results from Australia's National Greenhouse Gas Inventory[13,14] indicate average annual sequestration in post-1990 plantations over the period 2010-2020 of 14.2 Mt $CO_2$-e $yr^{-1}$. For pre-1990 plantations, the average over the last 10 years shows a net emission (2.7 Mt $CO_2$-e $yr^{-1}$), reflecting a decline in the rate of replacement of older plantation forests. The overall result is a net sequestration of 11.5 Mt $CO_2$-e $yr^{-1}$. This value includes sequestration in living biomass, forest debris and soil organic carbon, but excludes carbon stored in harvested wood products.

[13] National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

[14] Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

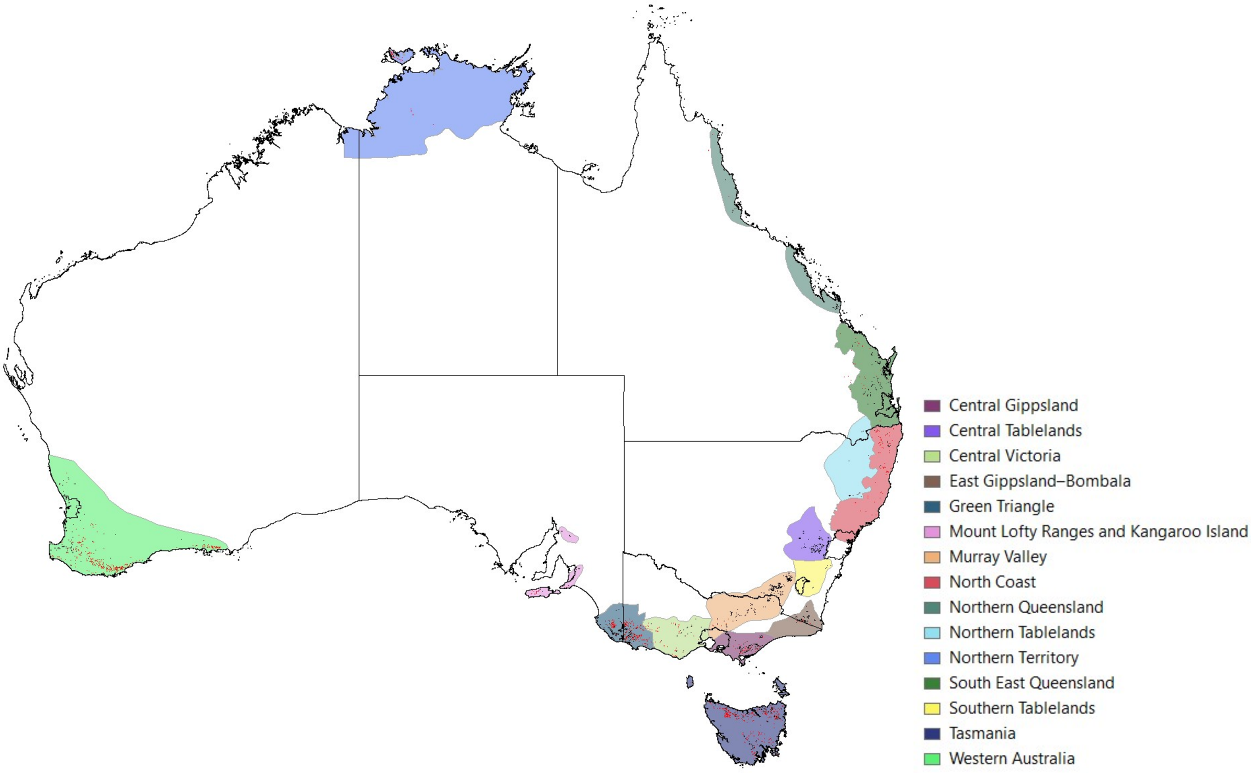



**Figure 5-2:** National Plantation Inventory regions in Australia. Within each NPI region red areas are the current distribution of hardwood plantations, and black areas are the distribution of softwood plantations (SOFR 2018).

## 5.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt.yr [1]) | Key evidence |
|---|---|---|
| **Technical Potential** | 631.34<br>(42.5) | Based on spatial modelling to identify potential areas for future activity, and FullCAM simulations to calculate sequestration potential (Roxburgh et al. 2020a). |
| **Economic potential by 2025** | NA | |
| **Economic potential by 2035** | NA | |
| **Economic potential by 2050[1]** | 31.77<br>(0.63) | Based on discounted cash flow modelling of the technical sequestration results, with an assumed carbon price of \$30 t $CO_2$-e, and a discount rate of 10% (Roxburgh et al. 2020a). |

[1]The economic sequestration calculation did not consider the possible time course of delivery, nor the staggering of new projects over time, hence no time course of ACCU delivery is provided. The economic sequestration value represents the maximum sequestration achievable assuming all new potential projects could be established over the near term (e.g., the next 1-2 years).

**Table 5-2: Best estimate of plantation forestry and farm forestry sequestration potential, with results for farm forestry given in parenthese. Sequestration for the plantation forestry and farm forestry activities are not spatially independent, given the overlapping land areas on which these activities can take place. This means the separate estimates for plantation forestry and farm forestry cannot be summed to provide a total sequestration estimate.**

### 5.3.1 Technical sequestration

#### Plantation forestry

Sequestration under the *Plantation Forestry* methodology is calculated using the FullCAM model, and includes carbon stored in above- and below ground living and dead biomass, and carbon stored in harvested wood products. For conversion projects the baseline sequestration is calculated as the difference between average FullCAM outputs over a 100-year period for the 'business as usual' short rotation plantation species, and the average FullCAM outputs over a 100-year period for the 'project' long-rotation species. For new plantations, sequestration is the average FullCAM predicted sequestration over a 100-year period for the planted species.

#### Plantation forestry - Conversion of short rotation to long-rotation plantations

Short rotation plantation species in Australia are predominantly the hardwoods *Eucalyptus globulus*, *E. dunnii* and *E. nitens*, and therefore the technical sequestration extent for short rotation conversion projects comprises the subset of current hardwood plantations within each NPI region that are established as short rotation. The percentage of short rotation hardwood area for each NPI region was obtained from an analysis of the current plantation systems in Australia (Downham and Gavran 2019). To define the potential extent, for each NPI region grid cells within the hardwood plantation extent were selected at random until the required area was attained (Figure 5-3a). Because the precise locations of the short rotation plantations were unknown, no analysis was undertaken to ensure the requirement of consistency in plantation management over the previous seven years.

#### Plantation forestry - New plantation establishment

The potential area for new plantation establishment included all freehold lands within NPI regions that are currently used for cropping or are grazed modified pastures, and that are not existing ERF projects. Freehold land tenure was defined by the Australian Land Tenure (1993) database. Limiting the available non-forested agricultural land within the NPI regions to freehold tenure assumes that new or expanding plantation estates would require the purchase of new land. The procedure adopted here for identifying the feasible extent for new plantation establishment required a continental-scale approach and was by necessity relatively simplistic (Figure 5-3b).

#### Farm Forestry

Under the *Measurement Based Methods for New Farm Forestry Plantations* methodology sequestration is calculated by field measurement, although for harvested plantations the FullCAM model is used to simulate the project activity for 100 years, from which average long-term sequestration is calculated. Although commercial harvesting is allowed under the methodology, in contrast to the *Plantation Forestry* (2017) methodology, the carbon stored in wood products is excluded from the sequestration calculation. To approximate sequestration achievable by field-based measurement, the FullCAM model is used as the basis for calculating technical sequestration, assuming establishment of a softwood plantation.

The technical sequestration extent was based on that calculated for the Permanent Plantings section 4.3. In summary, the extent is defined by current land use (non-forested land classified as either grazed modified pastures, dryland cropping, irrigated pastures, or irrigated cropping), with the potential to eventually support forest cover, and with current ERF project areas excluded.

The area was further limited to that with an annual average rainfall greater than 600mm, consistent with the climatic suitability for commercial plantation establishment (Polglase et al. 2013; Matysek and Fisher 2016). The water interception requirements for planting trees in areas greater than 600mm rainfall also apply to the establishment of commercial species as part of a farm forestry project, however these requirements were not considered here given the strict project size limitation of 100ha in areas in excess of 400mm rainfall, and the focus of the method on establishing trees within the matrix of an existing agricultural enterprise.

Because of the rainfall-based project size limits specified by this method, a further filtering was applied to represent this constraint. This was important, as the project size limits have the potential to impact financial viability through reducing the opportunities of reducing costs by economies of scale (i.e., fixed project costs are relatively more constraining in small compared with large projects) (Figure 5-3c)

Intersecting the areas in Figure 5-3 with the FullCAM modelling yielded the technical sequestration estimates in Table 5-3. For simplicity, for the plantation forestry estimates the five separate analyses were combined (short hardwood rotation to long hardwood or softwood rotation; new long-rotation softwood and hardwood rotations, and new hardwood short rotations)

| Planting type | 25yr sequestration (Mt $CO_2$ e) | 25yr annual average (Mt $CO_2$ e yr $^{1}$) | Area (MHa) |
|---|---|---|---|
| **Commercial plantations** | 15783.38 | 631.34 | 20.75 |
| **Farm forestry** | 1061.98 | 42.48 | 3.86 |

**Table 5-3: Technical sequestration associated with the Plantation Forestry Farm Forestry methodologies.**

The level of confidence in the overall sequestration estimates is medium. The FullCAM model is well calibrated for commercial tree species, and hence the confidence in the overall sequestration quanta is high, although the level of confidence in the spatial extent is medium, hence and overall medium rating. The level of confidence in pixel-level sequestration estimates is low.

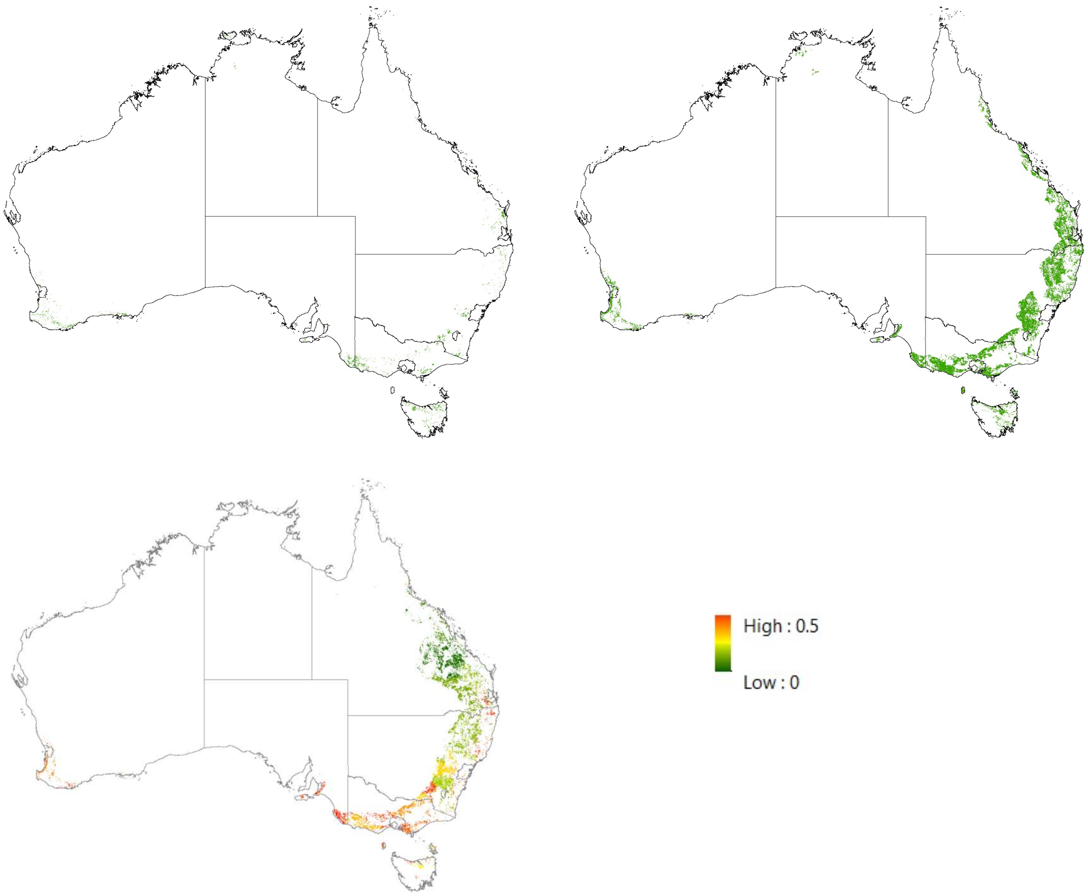



**Figure 5-3:** (a) Potential area for the conversion of short- to long-rotation projects under the Plantation Forestry methodology. Values are the probability of a given project extent being selected across 1000 random Monte Carlo re-samples (b) Potential area for new plantation establishment under the Plantation Forestry methodology. (c) Potential extent of possible future new farm forestry plantations.

### 5.3.2 Economic sequestration

It is important to differentiate between the area of land that is assessed as potentially being able to support new plantings, and that is realistically available and that could be planted – the economic sequestration subset. Consistent with prior work (Eady et al. 2009), a financial filter was applied to limit the technical sequestration areas to the economic potential subset. Economic viability was based on the direct and the opportunity costs of undertaking activities, compared against the expected revenues. Discounted cash flow modelling was applied, whereby locations were flagged as being likely to transition to carbon farming if the net present value (NPV) of the carbon farming activity, inclusive on income from harvested wood products in the case of the Plantation forestry method, exceeded current profitability. Under the current ERF methodologies, an important consideration is the possible requirement for projects in locations above 600 mm rainfall to purchase water rights, to offset removals from the growing plantations – the "water rule". Whether a plantation is required to purchase water is determined by state regulations (Indufor 2014). If projects are required to hold a water entitlement, the volume of water required as an offset is 1-2 megalitres (ML) per hectare per year, with about 1ML required in low rainfall regions and 2ML required in high rainfall regions. This has a significant cost: about \$5,500 $ML^{-1}$ for high reliability entitlements in the Murray-Darling Basin, with moderately lower prices in other regions. In undertaking these analyses, it was found that even assuming a low offset cost of \$2,500 $ML^{-1}$ made new plantations economically unviable in all regions at carbon prices of $0-100. As such, the only economically viable new plantations would be those that the regulation exempts from the requirement to purchase water offsets. In the results below, it was assumed that 50% of eligible locations would be required to purchase water offsets. Note that the recently elected Australian government has committed to removing the water rule, as a mechanism to reduce barriers to plantation tree expansion[15].

The cost assumptions are summarised in Table 5-5 below. Full details of the economic modelling are provided in Roxburgh et al. (2020a). Because the economic sequestration is sensitive to the assumed carbon price, minimum and maximum values are presented, corresponding to carbon prices of $15 t $CO_2$-e and $30 t $CO_2$-e, respectively. For the economic analysis a discount rate of 10% was applied on the basis it represents a typical rate used by private enterprises in evaluating investment opportunities (Roxburgh et al. 2020a). A subset of the Roxburgh et al. (2020a) plantation forestry analyses also assumed a 7% discount rate (although only the 10% results are shown here). Roxburgh et al. (2020a) interpreted the 10% discount rate as indicative of yielding viable carbon prices in the absence of State and other support, with the 7% discount rate closer to capturing the carbon prices that make projects viable under the continuation of additional financial support.

Given the existing plantation forestry estate is currently approximately 2M ha, and that expansion of new plantations over recent decades has ceased (leading to the development of two ERF methodologies, where new plantation establishment is no longer considered 'business as usual'), then the predicted areal increase of 2.7 – 9.8 Mha over 25 years in Table 5-4 would seem overly ambitious. This undoubtedly reflects a range of constraints that were not included in the modelling, such as changing demand for products, the influence of commodity prices, and perhaps most importantly, an assumption that all land area identified as financially viable could be procured and converted to plantation forestry. The National Forests Industry Plan (Department of Agriculture and Water Resources (2018)) specifies a target of an additional 0.4 Mha by 2030. Assuming that over the next 25 years an additional 1 Mha could be achieved, and assuming that this is evenly split across all the NPI regions, then this leads to revised economic sequestration totals of 29.32 – 31.77 Mt $CO_2$-e $yr^{-1}$.

A similar calculation can be applied to the Farm Forestry estimate, whereby following Eady et. Al. (2009) the assumption is made that 5% of landholders might consider changing practices to carbon farming. This yields a revised economic sequestration estimate of 0.43 – 1.09 Mt $CO_2$-e $yr^{-1}$. Note that per ha sequestration rates for Farm Forestry are lower than that for Plantation Forestry, reflecting differing assumed species, extension of growth into more arid areas, and exclusion of harvested wood products from the Farm Forestry calculation. Note also that, because of the project size limitations implicit in the analysis, this does not imply that 5% of the potential land area could be planted, but rather, 5% of properties, each with up to 100ha, could be converted. This 5% assumption is clearly simplistic, and requires refinement through further analysis that takes a more considered approach to key drivers, such as the social acceptance of landholders to integrate trees within their farms (Fleming et al. 2019).

---

[15] https://www.alp.org.au/policies/a-future-grown-in-australia

**Table 5-4:** Economic sequestration associated with the Plantation Forestry and Farm Forestry activities. The ranges reflect two carbon price assumptions, \$15 t $CO_2$-e (lower bound) and \$30 t $CO_2$-e (upper bound). Modelling of economic sequestration for Farm Forestry (without project area constraint) has not yet been undertaken. Note no 25yr sequestration estimate is provided for the Plantation Forestry methodology, given sequestration under this methodology is integrated over a 100-year timeframe, then apportioned equally over 15 years.

| Planting type | 25yr sequestration (Mt $CO_2$ e) | Annual average (Mt $CO_2$ e $yr^{1}$) | Area (MHa) |
|---|---|---|---|
| **Plantation Forestry** | - | 77.68 - 311.56 | 2.649 - 9.806 |
| **Plantation Forestry (expansion limited to 1Mha)** | - | 29.29 – 31.77 | 1.00 |
| **Farm forestry** | 106.7 – 313.6 | 4.27 – 12.54 | 0.357 – 0.881 |
| **Farm forestry (limited to 5% of total area)** | 5.34 – 15.68 | 0.21 – 0.63 | 0.018 – 0.044 |

# 5.4 Technology Readiness Potential and Commercial Readiness

## 5.4.1 Technology Readiness

| Technology Readiness | \$ per tonne $CO_2$e | Key Evidence |
|---|---|---|
| **9** | ~10-30 | Only direct costs of undertaking activities are included in the price, and include tree planting (varies by species), starter fertiliser (\$400 $ha^{-1}$), weed control (\$400 $ha^{-1}$), windrow and burn (\$400 $ha^{-1}$), pruning (\$400 $ha^{-1}$, timing varies by species), mid-rotation fertiliser (\$400 $ha^{-1}$, timing varies by species), thinning, harvesting, product haulage (all varying by species), and transaction costs (assumed to be 25% of achieved sequestration). Averaged over the total potential extent, and across species x rotation options, the average annual costs were \$374 $ha^{-1}$. Costings were based on Matysek and Fisher (2016), and the model underpinning the results in Polglase et al. (2013) |

**Table 5-5: Technical readiness assessment for plantation and farm forestry**

**Explanation:**

There is an existing plantation forest industry.

## 5.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| **4-5** | Commercial forestry growth is an established industry in Australia, with many government- and privately-owned enterprises. However, the uptake of Plantation Forestry projects under the ERF is relatively modest, with 11 contracted projects. This expertise, knowledge and infrastructure could be readily applied in the for-harvest Farm Forestry situation as well, given similarity in site preparation requirements, species selection and maintenance. |

Table 5-6:Commercial readiness assessment for plantation and farm forestry

**Explanation:**

Whilst the technology for growing and harvesting plantation trees is well developed, the relatively low uptake suggests a number of existing barriers, particularly the cost of securing land in areas conducive to high productivity forestry. Farm forestry, where plantations are integrated into existing agricultural enterprises, would seem to offer significant potential, especially if some of the constraining features of the existing ERF Farm Forestry methodology relating to project size are relaxed. The fact plantation expansion had stagnated prior to carbon pricing suggests factors beyond the carbon market are limiting activity.

## 5.5 Scalability, Length of storage, Measurement and Verification

### 5.5.1 Scalability.

There is a large gap between economic potential and technical sequestration associated with this activity, partly driven by factors external to the carbon market (as noted in the previous section), but also driven by economics, where high initial upfront costs are particularly significant, as are the opportunity costs of changing production systems (Rooney and Paul 2017). An additional limitation is that tree planting in agricultural landscapes involves a trade-off between land used for producing food, and land used for carbon farming. The potential land area identified above includes all available agricultural land within the constraints of each methodology. In reality, only a small proportion of this would ever be converted into tree plantings, given the ongoing need to feed human populations.

An additional challenge is the dispersed nature of the plantation estate in Australia, with implications for the economics of operations and the location of processing facilities. When forest estates can be concentrated in relatively close proximity then there is the potential for efficiencies in product transport and opportunities for the development of local processing and export infrastructure and industries.

### 5.5.2 Length of storage

As with Permanent Plantings, the majority of risks associated with establishing and managing plantation forests are associated with rates of sequestration, arising from reductions in tree growth from persistent increases in temperature, persistent increases in water stress, and disturbances from heat-stress and droughts arising from a changing climate (Roxburgh et al. 2020b). The greatest risk period is soon after planting or germination, when plants are young and more vulnerable to climatic stress. Wildfires are a risk factor to permanence, and pests and diseases are another permanence risk factor that has the potential to impact both young and mature forests (Pinkard et al. 2011). Adaptation options include varying planting species and genetic stock, altering planting configuration to reduce risks of resource limitations, careful site preparation and timing of establishment, and fire risk reduction management. Selective breeding for genotypes that confer increased resilience to climate extremes is also a response option.

### 5.5.3 Measurement and Verification

Integrity of the sequestration is high, with measurement and verification processes well developed, and the sequestration readily observable from the ground, and from aerial imagery and remote sensing.

## 5.6 Social, environmental impacts, risks and co-benefits

### 5.6.1 Social impacts and risks

Competition with existing land uses (particularly agriculture) can be an issue, particularly in areas of high productivity that are suitable for growing both high-quality timber as well as agricultural products. The social acceptance of an expanding plantation forest industry, particularly into predominantly agricultural landscapes, may prove challenging.

### 5.6.2 Environmental impacts and risks

Although plantation forestry has been shown to provide positive biodiversity and habitat benefit opportunities, there is also the possibility of adverse environmental outcomes, especially associated with the establishment of exotic plantation species, and associated risks of the unwanted spread of individuals beyond the plantation boundary. Also on the negative side, growing forests can reduce water yield as a result of increased transpiration, and hence can have detrimental impacts on catchment hydrology. For this reason, there are currently in place requirements for purchasing water licences in some areas when establishing plantation forests, although the current government has committed to removing this requirement to help promote plantation expansion.

### 5.6.3 Co-benefits

As with Permanent Plantings, plantation forests have the potential to provide biodiversity habitat through increasing landscape connectivity and vegetation complexity and can help ameliorate salinity. There are also clear economic and social benefits of promoting a regionally based, viable and expanding plantation industry.

## 5.7 Barriers to implementation:

### 5.7.1 Policy and regulatory environment

There are strict rules and regulations regarding the establishment of extensive new forested areas in most parts of Australia, for example relating to NRM planning, impact on amenity values (both positive and negative), and potential impacts on catchment water flows. These place an additional regulatory burden, on top of the requirements for entering into carbon farming. Relaxation or removal of the current project size limitations under the Farm Forestry methodology would also remove a significant existing barrier to undertaking farm forestry projects.

### 5.7.2 Social licence and stakeholder acceptance

The long history of plantation forestry in many regions of Australia has led to broad social acceptance in these areas, for example the Green Triangle region of Victoria and South Australia. However, expansion of plantation forests into new regions, in the form of either farm forestry or commercial plantations, is likely to be met with a varied response, particularly with respect to perceptions of replacement of agriculture by tree farming. Like shelterbelts, careful planning and placement of trees in landscapes to avoid adverse impacts and to promote co-benefits, will help mitigate these concerns.

### 5.7.3 Technology performance variability

Carbon outcomes from planting trees is inherently variable, both across space (due to variation in soil type, landscape position, etc.) and time (due to climatic variability, disturbances such as fire, etc.). As such this adds an element of risk to the activity.

### 5.7.4 Financial proposition and costs and access to capital

The major barriers to implementation are most likely to be economic, such as transport costs for wood products, the increasing price and availability of suitable production land, the non-performance of existing plantations potentially limiting reinvestment, the availability of processing plants, and in some cases the requirement for building new processing plants in newly developed plantation areas.

### 5.7.5 Industry supply chains and skills

A key limitation of establishing forest plantations is access to processing facilities for harvested wood products. Traditional sawmills are concentrated near existing plantation growth areas, and transport costs to get product to market are significant. Skills in establishing and maintaining for-harvest forests may not be present in novel regions outside of where traditional plantation forestry activity has historically taken place, particularly in the context of farm forestry. This could also be a market opportunity.

### 5.7.6 Market opportunities or market creation

One market opportunity is the development and establishment of novel uses for wood-based products, such as bioenergy, biochar, and the extraction and use of aromatic oils. Extending for-harvest plantations beyond the current spatial extent will require development of and access to new processing plants in these new regions for them to be economically viable.

## 5.8 Scaling knowledge gaps

- Expansion of the analyses presented in this section to include a broader range of carbon prices, land eligibility, and activities such as those associated with new market development.
- The social aspects of landholder and community acceptance and decision making is an important dimension impacting both current and future activity. A deeper review of these issues would help to better assess their contributions to scaling.
- The analyses presented here are tied to constraints of the 2017 Plantation Forests methodology, and the constraints of the farm Forestry methodology, and the requirement to purchase water offsets in certain circumstances. Further work is required to generalise the activities to be more representative of current and potential future for-harvest plantation activities, including the current government’s commitment to remove the requirements to purchase water offsets.
- Re-analysis of the farm forestry scenarios, with relaxation of the current project size limitations, and a more considered approach to determining the feabile area of land would also provide a more realistic assessment to total sequestration potential under this activity. Such a re-analysis would involve integrating both the social and the economic aspects of decisions to integrate trees into agricultural landscapes.

## 5.9 Chapter References


Department of Agriculture and Water Resources (2018). Growing a better Australia – A billion trees for jobs and growth, Canberra. CC BY 4.0. ISBN 978-1-76003-174-9 (printed).

Downham R. & Gavran M. (2019) Australian plantation statistics 2019 update. Research by the Australian Bureau of Agricultural and Resource Economics and Sciences. Technical report 19.2. https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/abares/publications/AustPlantationStats_2019_v.1.0.0.pdf.

Eady, S. et al. (2009) *An Analysis of Greenhouse gas Mitigation Opportunities from Rural Land Use*. CSIRO.

Fleming A., Stitzlein C., Jakku E. & Fielke S. (2019) Missed opportunity? Framing actions around co-benefits for carbon mitigation in Australian agriculture. Land Use Policy 85, 230-8.

Guo, L.B. & Gifford, R.M. (2002). Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345-360.

Indufor (2014) Guidance on the likely establishment of new timber plantations in Australia. Report for the Department of the Environment. Retrieved via: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.environment.gov.au%2Fsystem%2Ffiles%2Fconsultations%2F7c629a49-0d6f-430e-b6e2-2a9655df56c0%2Ffiles%2Fguidance-new-timber-plantations-establishment.docx

Matysek, A. & Fisher, B. (2016) The Economic Potential for Plantation Expansion in Australia. *Report to the Australian Forest Products Association*. Retrieved via: https://ausfpa.com.au/wp-content/uploads/2016/02/BAEconomics-plantations-report.pdf

Pinkard E. A., Battaglia M., Roxburgh S. & O'Grady A. P. (2011) Estimating forest net primary production under changing climate: adding pests into the equation. Tree Physiology 31, 686-99.

Polglase P. J., Reeson A., Hawkins C. S., Paul K. I., Siggins A. W., Turner J., Crawford D. F., Jovanovic T., Hobbs T. J., Opie K., Carwardine J. & Almeida A. (2013) Potential for forest carbon plantings to offset greenhouse emissions in Australia: economics and constraints to implementation. *Climatic Change* **121**, 161-75.

Rooney, M & Paul, K (2017). Assessing policy and carbon price settings for incentivising reforestation and regrowth activities in a carbon market: An Australian perspective. Land Use Policy 67, 725-732.

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020a) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, p. 425.

Roxburgh Stephen H., Paul K. & Pinkard E. (2020b) Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF). Report for the Climate Change Authority. p. 224.

Turner, J. & Lambert M. (2000). Change in organic carbon in forest plantation soils in eastern Australia. Forest Ecology and Management. 133, 231-247.

# 6 Human induced Regeneration of Native Forest

| Emission Type | Avoided | Negative |
|---|---|---|
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Table 6-1: Human induced regeneration of native forest technology type**

## 6.1 Summary

**Description and current uptake**

Human induced regeneration of native forest involves implementing changes in the management of non-forested land that promotes the establishment of native forest cover. Examples of management changes include ending historical land clearing, reducing rates of domestic livestock grazing and controlling feral browsers and grazers. Across Australia's managed forests the greatest sequestration potential is in arid and semi-arid woodlands that are primarily managed for rangeland grazing. The results from the analysis include estimates of sequestration that is consistent with that achievable under the ERF Human Induced Regeneration methodology that includes vegetation that meets Australia's forest definition (potential height >2m tall and canopy cover > 20%) and thus includes most of Australia's forest and woodland ecosystems), but does not include additional sequestration that could be achieved by restoring currently degraded forests or shrublands, or changes in soil organic carbon. Further research is required to provide estimates for these latter two components.

Based on Australia's National Greenhouse Gas Inventory, current uptake indicates average annual sequestration in naturally regenerating forests across Australia, over the period 2010-2020, of 20 Mt $CO_2$-e $yr^{-1}$ (inclusive of living biomass, debris and soil carbon).

**Sequestration potential**

Technical sequestration associated with native regeneration of native forest is 60.1 Mt carbon dioxide equivalents ($CO_2$-e) per year (25-year annual average) covering 32.2 Mha. At a carbon price of $30 t $CO_2$-e, the economic sequestration was estimated as 39.2 Mt $CO_2$-e per year (25-year annual average) at a cost of $5 per tonne.

**Technology readiness potential and commercial readiness**

The HIR methodology is popular and widespread, accounting for more than 50% of Australia's total contracted greenhouse gas (GHG) sequestration under the ERF. This uptake demonstrates a high commercial readiness for technologies involved in native forest regeneration. The relative profitability is mainly due to low upfront and opportunity costs.

**Scalability, length of storage, measurement and verification**

Activities associated with regeneration of native forest are readily scalable, with low fixed costs that are independent of project extent, and minimal costs associated with project establishment and maintenance.

From the sequestration perspective, the main risks to storage are associated with changes in the climate that affect the survival of young regenerating stands and the growth rates of mature stands. These can include changes in average and maximum temperature, which have the potential to reduce net primary productivity and carbon sequestration rates. The main risk factor to permanence is mortality associated with extreme drought.

Because regenerating native forest involves increasing the cover and density of trees across the landscape, sequestration is readily visible from the ground and from space. Sequestration can be measured directly via field measurement or estimated indirectly via modelling based on remotely sensed data.

**Social, environmental impacts, risks and co-benefits**

The large spatial extent of current and future native forest regeneration activities may change trends in farm management, especially in marginal production areas, and this could have a social impact. Environmental risks include the potential for regenerating forests to provide habitat for exotic species, increased fire risk (through increasing fuel loads) and reduce overall landscape-scale water availability (through intercepting runoff).

There are environmental benefits associated with restoring native forest, such as biodiversity recovery (through improved habitat quality and extent for native fauna and flora). Increased ground cover can lead to improved soil condition, reduced runoff and soil stabilisation. Social co-benefits include increased farm profitability through expanded and diversified income streams, increased employment opportunities and the potential to re-vitalise rural communities.

**Barriers to implementation**

Strong policy support and an established regulatory environment already exist for activities that regenerate native forest. Their widespread adoption under the ERF suggests both broad stakeholder acceptance and an accompanying social licence. While concerns have been raised about potential negative impacts, from April 2022 the federal minister for agriculture has the power to prevent native forest regeneration projects from going ahead if they are deemed to have an adverse impact on agricultural production or regional communities.

Technology performance is unlikely to be a barrier to implementation. Natural regeneration of native forests has relatively low start-up costs, and the majority of current activity occurs on land with relatively low productivity. Regeneration activities are already supported by the ERF and its associated market mechanism.

**Scaling knowledge gaps**

Further research should investigate the impacts, risks and benefits (positive and negative) of regenerating native forests in both social and environmental contexts. This research would help minimise the potential for negative outcomes and provide a sound basis for recognising and rewarding positive benefits. In addition, future analyses should include a broader range of carbon prices and land eligibility, including extending analyses to include management of existing degraded forests, and soil organic carbon.

**ENABLERS**

- Targeted investigation and quantification of the social and environmental impacts and risks
- Further economic analysis at different carbon prices

**CO-BENEFITS**

- Biodiversity benefits
- Improved soil condition
- Reduced erosion
- Increased farm profitability

**Actual 2010-20**
**20 Mt per year**

**Technical potential**
**60 Mt per year**

**Economic potential**
**39 Mt per year**

**BARRIERS**

- Concerns with change of conventional landuse and potential impacts on communities
- Concerns with measurement and verification of sequestration

**RISKS AND IMPACTS**

- Disruption to traditional land use
- Potential for increased exotic species
- Concerns with increased fire risk
- Sequestration rates affected by drought and fire

**TRL: 9 CRL: 5-6 Cost: ~$5 per tonne Length of storage: 25-100 years**

**Figure 6-1: Summary of human induced regeneration of native forest sequestration. Actual sequestration reflects sequestration in all regenerating native forests in Australia over the period 2010-2020, as reported in Australia's annual National Greenhouse Gas Inventory. Actual sequestration includes soil carbon as well as living biomass and forest debris, whereas the Potential and Economic potential estimates include only living biomass and debris.**

## 6.2 Description and current uptake

Human induced regeneration of native forest involves implementing a change in the management of non-forested land that promotes the establishment of native forest cover, and where current land management is actively suppressing forest recovery. Note that while both human induced regeneration of native forest and avoided land clearing (Chapter 7) can involve the cessation of land clearing, human induced regeneration involves promoting the re-establishment of forest cover on land where tree recovery is currently being suppressed, whereas avoided land clearing involves the cessation of future clearing of land that has been cleared historically, but has re-grown and currently meets the Australian forest definition for height (>2m) and canopy cover (>20%).

Examples of land management changes that promote forest recovery include cessation of land clearing (either mechanically, or through herbicide application), reduction in rates of domestic livestock grazing, and control of feral browsers and grazers. Across Australia's managed forests the greatest sequestration potential is in the arid and semi-arid woodlands that are primarily managed for rangeland grazing, and that have been subject to intensive vegetation management in the past, particularly repeated removal of tree cover to promote pasture growth for livestock production. Although tree canopies in these ecosystems are typically sparse, they are extensive enough in both height (>2m tall) and canopy cover (> 20%) to meet Australia's forest definition.

Results reported in Roxburgh et. al. (2020a) were used to provide estimates of future sequestration associated with natural regeneration of native forests. As the analyses in that report were specific to sequestration that could be achieved under current relevant ERF methodologies, they should be considered a conservative assessment of sequestration that could be achieved more generally. Additional lands that were excluded from that analysis, but which could also be managed to increase carbon stores, include (a) forested areas that are currently degraded, but could be restored. Although not strictly forest regeneration, such areas are potentially a valid source for future sequestration activity, and could include the recovery of previously harvested native forests in more mesic environments (e.g. Roxburgh et al. 2006; Mackey et al. 2022); (b) areas that had forest cover within the required 10-year non-forest period specified by the ERF methodologies; (c) inclusion of non-forest woody vegetation, such as shrublands; and (c) small isolated areas that are unlikely to support ERF project activity, but which could support forest regeneration. The analyses summarised below also exclude changes in soil carbon, given uncertainty associated with changes in soil carbon following native forest management. Inclusion of these aspects to extend the current work would require extensive new analysis.

Within Australia's ERF there are two methodologies that involve the regeneration of native forest: *Human Induced Regeneration of a Permanent Even-Aged Native Forest* (HIR) and *Native Forest from Managed Regrowth* (NFfMR). Both methodologies require projects to promote the natural regeneration of native vegetation through management changes that remove pressures that are preventing the establishment of forest cover. Under the HIR methodology, ACCUs are awarded based on a change in management that allows a forest to re-grow, with subsequent accounting of the accumulation of carbon in the recovering vegetation and forest debris over time, and with forest cover required to be achieved within 15 – 20 years from the commencement of regeneration. The NFfMR methodology operates by a similar mechanism but is targeted towards lands that are currently being actively cleared, with one of the key requirements being evidence for at least one past clearing event. Another difference between the two methodologies is that some level of woody vegetation is allowed during the baseline period for NFfMR, with a requirement to account for this baseline biomass in the sequestration calculation. To provide a spatially consistent and comprehensive estimate of potential and economic sequestration, only the HIR results are used for the total sequestration figure below, with the NFFMR results included for completeness.

To provide an indication of current rates of sequestration under natural regeneration, results from Australia's National Greenhouse Gas Inventory[16], with values extracted from the AGEIS online database[17], indicate average annual sequestration, over the period 2010-2020, of 20 Mt $CO_2$-e $yr^{-1}$ (inclusive of living biomass, debris and soil carbon).

## 6.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt.yr $^{1}$) | Key evidence |
|---|---|---|
| **Technical Potential[1]** | 60.1 | Based on spatial modelling to identify potential areas for future activity, and FullCAM simulations to calculate sequestration potential (Roxburgh et al. 2020a). |
| **Economic potential by 2025[2]** | NA | |
| **Economic potential by 2035[2]** | NA | |
| **Economic potential by 2050[3]** | 39.2 | Based on discounted cash flow modelling of the technical sequestration results, with an assumed carbon price of \$30 t $CO_2$-e, and a discount rate of 10% (Roxburgh et al. 2020a). |

[1]The technical sequestration area excludes land occupied by current ERF projects undertaking HIR or NFfMR. Only the HIR total is shown, as the potential land area for NfFMR is a small subset of that for HIR.
[2]The economic sequestration calculation did not take into account the possible time course of delivery, nor the staggering of new projects over time, hence no time course of ACCU delivery is provided.
[3]The economic sequestration value represents the maximum sequestration achievable assuming all new potential projects could be established over the near term (e.g. the next 1-2 years)

**Table 6-2: Best estimate of Natural Regeneration of Native Forest sequestration potential**

### 6.3.1 Technical sequestration

For both the HIR and NFfMR methodologies the FullCAM model was used as the basis for the sequestration calculation, with the FullCAM forest growth equations applied continentally at a spatial resolution of 250 m x 250 m.

#### HIR

To provide a comprehensive library of model results on which to base further analyses, FullCAM spatial growth predictions of combined above- and below ground living biomass and forest debris were saved annually from year 0 (with biomass and debris carbon stocks assumed to be 0.0) to year 30. The growth model calibrations used in the simulations were for native forest regeneration on lands managed for grazing ($Block_{LMG}$, Paul and Roxburgh 2020).

Whilst the FullCAM modelling provides a comprehensive 'wall-to wall' continental-scale library of forest regeneration potential, for analysis of sequestration potential it was necessary to mask out those areas that are either biophysically unsuitable (or otherwise unlikely) to support native forest regeneration activity.

[16] National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

[17] Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

This was achieved by progressively applying a set of six spatial filters. These filters were selected on the basis that they best reflect the biophysical and past management constraints that are most likely to support HIR activity. No attempt was made to model potential changes in this extent in response to future changes in climate, or other external drivers.

1. *Inclusion based on current land use*

   The first filter includes only land that is classified as grazed native vegetation, based on the Land Use of Australia 2010-2011 coverage (ABARES 2017). The assumption is that HIR activity is most likely to occur where there is current active management, and where there remains potential for natural forest regeneration – i.e. lands managed for grazing. Including only grazed native vegetation precludes some potential HIR areas that might be otherwise be eligible within conservation lands, but these were considered negligible given the continental-scale of the current analysis.

2. *Exclusion based on current forest cover*

   By definition, forest regeneration can only occur on land that is currently non-forested but has the potential to attain forest cover, therefore, areas of land that are currently forested were excluded from analysis. An additional ERF methodology constraint is that land must be non-forest for the previous 10 years, and this was also included in the analyses reported here. The dataset used was the National Forest and Sparse-Woody Vegetation Data version 3 (DoEE 2018a), with the 2018 coverage used to define current non-forested areas, and the historical record (2008-2018) to further check that the land had been non-forest for the previous 10 years. This dataset is provided at a high spatial resolution (approximately 25 m x 25 m continentally), and for data manageability was re-sampled to 250 m x 250 m, recording the total number of forested 25 m x 25 m grid cells within each target 250 m x 250 m grid cell.

3. *Inclusion based on potential to support forest cover*

   To differentiate land that is currently naturally non-forest (such as grasslands and shrublands), from land that is currently non-forest but has the potential to attain forest cover (and hence potentially eligible under the HIR rules), the National Vegetation Inventory System (NVIS) pre-1750 classification was used (DoEE 2018b). Only land that was mapped as potentially able to support forest cover was included.

4. *Proximity analysis: modified and transformed landscapes.*

   Recognising that HIR activity is not likely to occur in areas on largely intact or remnant vegetation, a proximity analysis was conducted to include only grid cells that were within 10 km of modified or transformed landscapes, as defined by the Vegetation, Assets, States and Transitions (VAST) v2. Classification (Lesslie et al. 2010).

5. *Proximity analysis: current forest cover*

   Recognising that HIR activity is not likely to occur in areas that are devoid of any existing forest cover (to provide confidence forest cover can be attained, and to ensure the presence of some forest regenerative capacity in the landscape), a proximity analysis was conducted to include only grid cells that contained more than 5% forest cover within a 10 km radius of the target grid cell.

6. *Exclusion of current HIR projects*

   Current ERF project areas (approximately 17.5M ha) were excluded from the analysis, on the basis they are either currently forested, or will attain forest cover in the immediate future - and are hence incompatible with additional forest regeneration activity.

Intersecting the above constraints resulted in a total potential area for potential future HIR activity of 32.3 Mha, and an average annual unconstrained sequestration capacity of 60.1 Mt $CO_2$-e $yr^{-1}$ after 25 years growth (Figure 6-2a).

### NFfMR

Because of the overlap between NFfMR and HIR in terms of prior land use, current land use, and allowable activities, the approach applied to the technical sequestration extent for HIR provided the basis for NFfMR. To recognise the additional NFfMR requirement to demonstrate that the land had previously been cleared of forest cover, only locations with evidence of a historical change in forest cover were included. The National Forest and Sparse-Woody Vegetation Data version 3 (DoEE 2018a) was used to identify such areas, whereby the 2018 coverage was used to identify current non-forested areas, and grid cells were included only if they were identified as supporting forest cover at least once in the period 1988-2017. For data manageability the forest cover dataset was re-sampled from 25m x 25m to 250 m x 250 m prior to analysis. Application of this deforestation constraint resulted in a total economic potential extent of 2.04 Mha (Figure 6-2b).

There are some caveats associated with this economic potential extent. First, although it includes all lands where vegetation cover is currently non-forest (i.e. at 2018) but with forest cover reported at least once in the past (1988 - 2017), no attempt was made to attribute that change to ensure only transitions due to human clearing were included. The economic potential extent therefore also includes forest-to-non-forest transitions due to other processes, such as natural mortality. Second, because of the limited period of the record, clearing events pre-1988 with no subsequent re-establishment of forest cover will not be identified. The first limitation will tend to overestimate the potential area available; the second limitation will tend to underestimate the area available. The degree of over- or under-estimation is unknown.

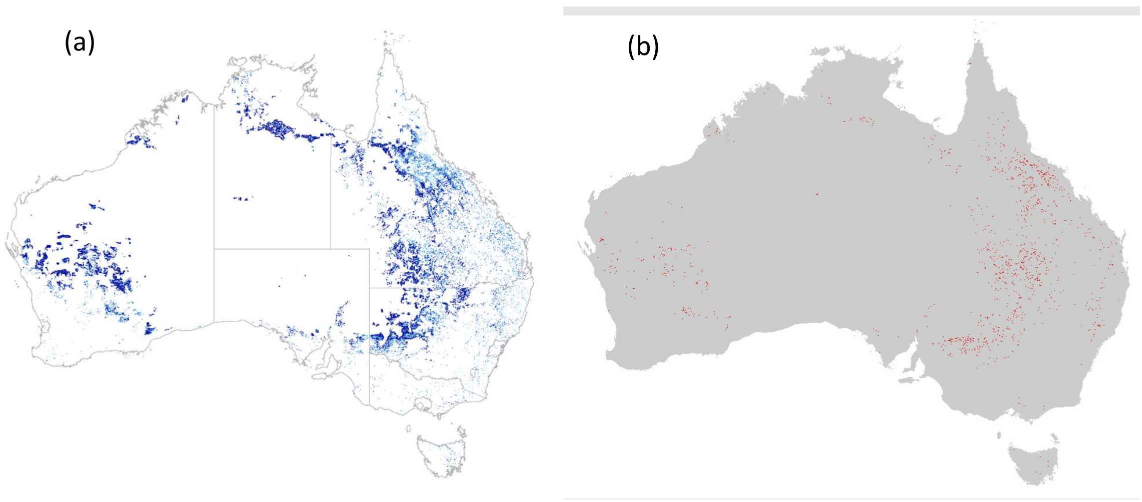



**Figure 6-2:.** (a) Potential extent of future HIR project activity. (b) Potential extent of future NFfMR project activity.

Intersecting the areas in Figure 6-2 with the FullCAM modelling yielded the technical sequestration estimates in Table 6-3.

| Planting type | 25yr sequestration (Mt $CO_2$ e) | 25yr annual average (Mt $CO_2$ e $yr^{1}$) | Area (MHa) |
|---|---|---|---|
| **Human Induced regeneration (HIR)** | 1502.5 | 60.1 | 32.3 |
| **Native Forest from Managed Regrowth (NFfMR)** | 128.5 | 5.1 | 2.04 |

**Table 6-3:Technical sequestration associated with the HIR and NFfMR methodologies for the areas identified in Figure 6-2.**

### 6.3.2 Economic sequestration

Under both the HIR and NFfMR activities it is important to differentiate between the area of land that is assessed as potentially being able to support new plantings, and that is realistically available and that could be planted – the economic sequestration subset. Consistent with prior work (Eady et al. 2009) a financial filter was applied to limit the technical sequestration areas to the economic potential subset. Economic viability was based on the direct and the opportunity costs of undertaking activities, compared against the expected revenues. Discounted cash flow modelling was applied, whereby locations were flagged as being likely to transition to carbon farming if the net present value (NPV) of the carbon farming activity exceeded current profitability. A third constraint for HIR was also introduced, after recognising that the technical sequestration extent (Figure 1) contains many areas with numerous individual small pixels (or groups of pixels) that are unlikely to be sufficient in extent to support a viable project. To address this, a further filtering was applied to remove areas that were below the limit of what is expected to support a minimum project extent. Full details of this adjustment, and the associated economic modelling, are provided in Roxburgh et al. (2020a). Because the economic sequestration is sensitive to the assumed carbon price, minimum and maximum values are presented, corresponding to carbon prices of $15 t $CO_2$-e and $30 t $CO_2$-e, respectively (Table 6-4).

Note that no consideration was given in the analysis to additional factors that could limit future uptake of natural regeneration of native forest activities, such as technological barriers, or sovereign risks such as interventions of the minister under the CFI Rule amendment designed to prevent regeneration projects from going ahead if they are deemed to have an adverse impact on agricultural production or regional communities. Note also that the values in Table 6-4 represent maximum economic potential potentials, as they do not consider the staggered introduction of new projects over time; rather, the values represent the economic sequestration that could be achieved if all possible new projects could be established over the short term (1-2 years). As discussed in the introductory section, only the HIR results are used for the final reporting, given the NfFMR activities are embedded within the HIR subset.

| Human Induced regeneration (HIR) | 25yr sequestration (Mt $CO_2$ e) | 25yr annual average (Mt $CO_2$ e yr $^{1}$) | Area (MHa) |
|---|---|---|---|
| **Human Induced regeneration (HIR)** | 652.07 – 980.81 | 26.08 - 39.23 | 14.50 – 22.46 |
| **Native Forest from Managed Regrowth (NFfMR)** | 111.03 - 120.51 | 4.44 – 4.82 | 1.86 - 2.01 |

**Table 6-4:** Economic sequestration associated with the HIR and NFfMR methodologies. The ranges reflect two carbon price assumptions, $15 t $CO_2$-e (lower bound) and $30 t $CO_2$-e (upper bound).

## 6.4 Technology Readiness Potential and Commercial Readiness

### 6.4.1 Technology Readiness

| Technology Readiness | $ per tonne $CO_2$e | Key Evidence |
|---|---|---|
| 9 | ~5 | Only direct costs of undertaking activities are included in the price, comprising project transactions costs (assumed to be 25% of achieved sequestration), and set up and annual maintenance costs (assumed to be |

| | |
|---|---|
| | \$1 $ha^{-1}$ $year^{-1}$ for the first five years, halving thereafter). |

Table 6-5: Technology readiness assessment for natural regeneration of native forest

**Explanation:**

Human Induced Regeneration is a popular and widespread methodology. The relative profitability is due primarily to low upfront costs, and low opportunity costs associated with current land management in the semi-arid areas in which the method is popular.

### 6.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| 5-6 | Widespread uptake of these methodologies demonstrates high commercial readiness. |

Table 6-6: Commercial readiness assessment for natural regeneration of native forest

**Explanation:**

Widespread uptake of these methodologies demonstrates high commercial readiness.

## 6.5 Scalability, Length of storage, Measurement and Verification

### 6.5.1 Scalability

Activities associated with regeneration of native forest are readily scalable, with low fixed costs that are independent of project extent, and minimal costs associated with project establishment and maintenance. Evidence for this can be seen in the uptake under the ERF, with large individual projects (average project area approximately 60,000 ha) and with an overall areal coverage of approximately 17.5M ha (Roxburgh et al. 2020a).

### 6.5.2 Length of Storage

From the perspective of sequestration accumulation, the main risks to storage are associated with changes in the climate that affects the survivorship of young regenerating stands, and the growth rates of mature stands. The main drivers are changes in average and maximum temperature, and the associated variables potential evapotranspiration and relative humidity, which have the potential to reduce net primary productivity, and hence rates of carbon sequestration. Regarding permanence, the main risk factor is from mortality associated with extreme drought, although the ultimate consequences for carbon sequestration are uncertain as they are a function of the combined rates of subsequent debris decay and other losses (such as from termites), and rates of post-drought recovery (Roxburgh et al. 2020b). The drought risk is exacerbated through the regional concentration of projects in northwest New South Wales, and southwest Queensland. Because fire is not a major feature in the areas where these activities have been established, or are likely to be established in the future, it is not considered a significant risk factor overall, although fire does occur within the region, and hence individual projects should have in place appropriate fire management plans. The key stage of vulnerability for these projects is during the establishment and early years of growth.

### 6.5.3 Measurement and Verification

Because the regenerating native forest activity involves increasing the cover and density of trees across the landscape, the sequestration is readily visible from both the ground and from space. Sequestration can therefore either be measured directly via field measurement or can be indirectly estimated via modelling based on remotely sensed data, or via terrestrial carbon models calibrated specifically for quantifying carbon in recovering vegetation, such as FullCAM (Paul and Roxburgh 2020). Field measurements across large spatial scales are logistically prohibitive, particularly given the high spatial variability of biomass characteristic of these environments, therefore measurement-informed modelling is both a robust and practical alternative.

Under the ERF, sequestration estimates are based on the FullCAM model, however project proponents are required to additionally demonstrate that forest cover is being achieved, e.g., through high resolution aerial photography or direct field measurement. These requirements, combined with a need to carefully stratify project areas to ensure existing forest, and land not capable of supporting forests in the future (e.g., salt-affected areas), are excluded from the accounting provides a strong integrity check that biomass is accumulating and forest cover is being achieved. Nevertheless, some technical elements of the way the methodology has been implemented have been recently criticised, sparking debate on whether sequestration in some contexts is truly additional (Mackintosh et al. 2021; Beare et al. 2021; Mackintosh et al. 2022).

In response, the Australian Government has commissioned an independent expert panel to review the integrity of Australian Carbon Credit Units (ACCUs) under the Emissions Reduction Fund. The Review will consider whether particular methods subject to recent claims – including the human-induced regeneration method – continue to comply with the scheme's integrity standards

## 6.6 Social, environmental impacts, risks and co-benefits

### 6.6.1 Social impacts and risks

The spatial extent of current and future natural regeneration of natural forest regeneration activities is significant at the continental-scale (Figure 6-3), and therefore has the potential to change trends in farm management over extensive areas, especially in marginal production areas where carbon farming might provide a more reliable income than traditional livestock farming.  There are therefore concerns associated with such widespread disruption to traditional farming practices that are social, environmental (for example to potential to facilitate increases in exotic species, and concerns over increased fire risk), and that are also related to the potential loss of agricultural productivity through reduced areas of grazing land. In response to these potential impacts, from April 2022[18] the federal minister for agriculture has had the power to prevent native forest regeneration projects from going ahead if they are deemed to have an adverse impact on agricultural production or regional communities.

### 6.6.2 Environmental impacts and risks

The key environmental risks were introduced in the previous section and include the potential for regenerating forest cover to provide habitat for exotic species; the potential for increased fuel loads across

[18] https://www.minister.industry.gov.au/ministers/taylor/media-releases/rule-change-protect-agriculture-and-regional-communities

the landscape to increase fire risk; and the potential for increased forest cover to intercept runoff and thus reduce overall landscape-scale water availability.

### 6.6.3 Co-benefits

In contrast to the risks discussed above, there are numerous benefits associated with the restoration of former native forest cover. These include the biodiversity benefits associated with the recovery of the native forest flora, and improved habitat quality and extent for native fauna. Additional environmental benefits include increased ground cover leading to improved soil condition, reduced runoff, and soil stabilisation. Social co-benefits include increased farm profitability through expanded and diversified income streams, increased employment opportunities, and the potential to re-vitalise rural communities (Bustamante 2014).

## 6.7 Barriers to implementation:

### 6.7.1 Policy and regulatory environment

As the most significant sequestration technology currently under the ERF, there already exists strong policy support and an established regulatory environment for natural regeneration of native forest activities.

### 6.7.2 Social licence and stakeholder acceptance

The widespread adoption of regenerating native forest activities across the continent under the ERF suggests both broad stakeholder acceptance, and accompanying social licence to operate, although some concerns have been raised regarding potential negative impacts on local communities, agricultural productivity and the environment (section 6.6.1 above). The extent to which the new ministerial powers will act to reduce the rate of future project uptake remains to be seen.

### 6.7.3 Technology performance variability

Variability in technology performance is unlikely to be a barrier to implementation for regenerating native forest activities, given the transparent and clear evidence of successful sequestration that can be directly observed, and the sound basis and high confidence on which key technological interventions (e.g., ceasing land clearing) are known to promote sequestration. Other interventions, such as reduced or modified grazing pressure, or management of feral populations, are less well documented scientifically, and may be spatially variable in the success of their application (Paul et al 2016).

### 6.7.4 Financial proposition and costs and access to capital

Natural regeneration of native forests has relatively low start-up costs, and most of the current activity occurs on relatively low productivity land, and hence the opportunity costs are also relatively low. Together, this combination of financial factors has made these activities profitable at relatively low carbon prices of < \$20 t$CO_2$-e and has supported rapid uptake. With increases in the carbon price, additional land areas in more productive regions are expected to become profitable, with expected expansion of projects into these regions.

### 6.7.5 Industry supply chains and skills

From a technological perspective, natural regeneration of native forests is a relatively straightforward and easy to implement solution, not requiring investment in complex machinery, nor specialist skills training to facilitate project implementation. Industry supply chains and skills are therefore unlikely to provide significant barriers to implementation.

### 6.7.6 Market opportunities or market creation

Natural regeneration of native forest activities are already supported by the ERF and its associated market mechanism, with ACCUs purchased either directly by government, or traded on the open market.

## 6.8 Scaling knowledge gaps:

Scaling knowledge gaps include:

1. Targeted investigation and quantification of the social and environmental impacts and risks, co-benefits and dis-benefits of regenerating native forests, to minimise the potential for perverse outcomes, and to provide a sound basis for recognising and rewarding positive benefits.
2. Expansion of the analyses presented in this section to include a broader range of carbon prices and land eligibility, beyond those that are consistent within the constraints of the ERF framework. This includes extending analyses to include forest degradation, non-forested woody ecosystems such as shrublands, and the inclusion of soil organic carbon.

## 6.9 Chapter References


ABARES. (2017) Land use of Australia 2010-11. https://data.gov.au/dataset/ds-dga-bba36c52-d5cc-4bd4-ac47-f37693a001f6/details.

Beare, S., Chambers, R. (2021). Human induced regeneration: A spatiotemporal study. Report for Clean Energy Regulator, Canberra. AnalytEcon Pty Ltd, Berry, NSW, Australia.

Bustamante M., Robledo-Abad C., Harper R., Mbow C., Ravindranat N. H., Sperling F., Haberl H., de Siqueira Pinto A. & Smith P. (2014) Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. Global Change Biology 20, 3270-90.

DoEE. (2018a) National Forest and Sparse-Woody Vegetation Data (Version 3, 2018 Release). Department of Environment and Energy, Commonwealth of Australia, Canberra

DoEE. (2018b) NVIS Major Vegetation Subgroups (Version 5.1). Department of Environment and Energy, Commonwealth of Australia, Canberra

Eady, S. et al. (2009) *An Analysis of Greenhouse gas Mitigation Opportunities from Rural Land Use*. CSIRO.

Lesslie R., Thackway R. & Smith J. (2010) A national-level Vegetation Assets, States and Transitions (VAST) dataset for Australia (version 2.0).

Macintosh, A., Butler, D., Ansell, D. (2022) Measurement Error in the Emissions Reduction Fund's Human induced Regeneration (HIR) Method. The Australian National University, Canberra.

Macintosh, A., Butler, D., Evans, M.C., Larraondo, P.R., Ansell, D., Gibbons, P. (2022) The ERF’s Human induced Regeneration (HIR): What the Beare and Chambers Report Really Found and a Critique of its Method. The Australian National University, Canberra.

Mackey B., Moomaw W., Lindenmayer D. & Keith H. (2022) Net carbon accounting and reporting are a barrier to understanding the mitigation value of forest protection in developed countries. Environmental Research Letters 17, 054028.

Paul K. I., England J. R., Roberts G., Roxburgh S. H., Prober S., Caccetta P., Cook G. & De Ligt R. (2016) Potential for carbon abatement through management of Australian woodlands. Report for the Department of Energy and Environment.

Paul K. I. & Roxburgh S. H. (2020) Predicting carbon sequestration of woody biomass following land restoration. *Forest Ecology and Management* **460**, 117838.

Roxburgh S. H., Wood S. W., Mackey B. G., Woldendorp G. & Gibbons P. (2006) Assessing the carbon sequestration potential of managed forests: a case study from temperate Australia. Journal of Applied Ecology 43, 1149-59.

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020a) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, p. 425.

Roxburgh Stephen H., Paul K. & Pinkard E. (2020b) Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF). Report for the Climate Change Authority. p. 224.

# 7 Avoided Land Clearing

| | | |
|---|---|---|
| **Emission Type** | Avoided | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Table 7-1: Avoided land clearing technology type**

## 7.1 Summary

**Description and current uptake**

Avoided land clearing aims to achieve carbon sequestration by retaining areas of native vegetation that would otherwise have been cleared. Sequestration is based on preventing existing 'mature' vegetation from being cleared or by stopping repeated clearing in vegetation that is recovering from past clearing event(s).

The analyses in this chapter are based on the Avoided Clearing ERF methodology, and thus the sequestration estimates exclude soil carbon, and include constraints associated with a requirement to demonstrate an unrestricted right to clear the land. Further analyses are required to extend the results presented here to include broader coverage of all lands subject to past clearing. No estimate of current uptake is available for avoided land clearing, due to difficulties in identifying land areas where deliberate decisions were made to cease clearing activity.

**Sequestration potential**

Technical sequestration associated with avoided clearing of native regrowth over an area of 1.38 Mha is estimated to be 9.2 Mt carbon dioxide equivalents ($CO_2$-e) per year (25-year annual average). At a carbon price of $30 t $CO_2$-e, economic sequestration associated with the methodology is estimated to be 7.74 Mt $CO_2$-e per year (25-year annual average) over 1.18 Mha at a cost of $5-$10 per tonne.

**Technology readiness potential and commercial readiness**

Avoided land clearing activities are well established and are similar to other activities associated with vegetation management, thus there are few technological barriers. The low number of ERF projects under this methodology suggest certain settings are not favourable to widespread roll out at this stage. Possible reasons for this include the strict requirements of the methodology.

**Scalability, length of storage, measurement and verification**

The difference between potential and economic sequestration is smaller for this activity than for other methods involving the management of vegetation, with approximately 80% of the technical sequestration deemed to be economic potential. The majority of the identified opportunity involves the management of Category 'X' vegetation in Queensland (Category X vegetation includes areas of regrowth not generally regulated by vegetation management legislation).

Avoided land clearing activities involve the protection of existing vegetation, so the risks to accumulation are low. The main risks associated with sequestration permanence are associated with extreme drought, and rates of post-drought recovery.

Because avoided land clearing involves increasing the cover and density of trees across the landscape, sequestration is readily visible from the ground and from space. Sequestration can be measured directly via field measurement or estimated indirectly via modelling or based on remotely sensed data.

**Social, environmental impacts, risks and co-benefits**

Most social impacts of avoided land clearing activities are related to reduced production (primarily beef) on land managed for regrowth. Impacts associated with this change could flow on to local communities that historically have been based on rangeland production rather than carbon farming.

Environmental impacts of retaining and increasing native forest cover are likely to be mostly positive (such as habitat restoration and biodiversity recovery). Additional impacts may arise from subsequent changes to the proportion of overstory (trees and shrubs) and understory (predominantly grasses) vegetation, with possible implications for accessibility, ground cover, surface erosion and runoff. In the areas most suited to the avoided clearing activity the fire risk is relatively higher than the natural regeneration of native forest activity, due to higher productivity and greater contiguity of ground fuels

In addition to sequestration of carbon and diversification of farm incomes, the primary co-benefits associated with avoided land clearing therefore involve ecosystem restoration.

**Barriers to implementation**

The policy and regulatory environment for implementing avoided land clearing of native regrowth technologies requires documented evidence for a number of criteria. Easing some of these restrictions might extend the area where the technology could be applied and increase the total technical sequestration. In general, preventing vegetation loss has stakeholder acceptance and social licence, but does come with concerns over changes to traditional land management.

Variability in technology performance is unlikely to be a barrier to implementation, the main technological intervention (ceasing land clearing) is known to protect carbon stores that would otherwise have been lost to the atmosphere. Avoided land clearing has relatively low start-up costs and removes the costs of any future clearing. The activities are relatively straightforward and easy to implement, not requiring complex machinery or specialist skills.

**Scaling knowledge gaps**

Further investigation is needed to expand the analyses to include a broader range of carbon prices and land eligibility, and to explore relaxing some of the regulatory assumptions underlying the current analysis. Given the identified economic viability and sequestration potential, future studies should look more closely at the current barriers to participation.

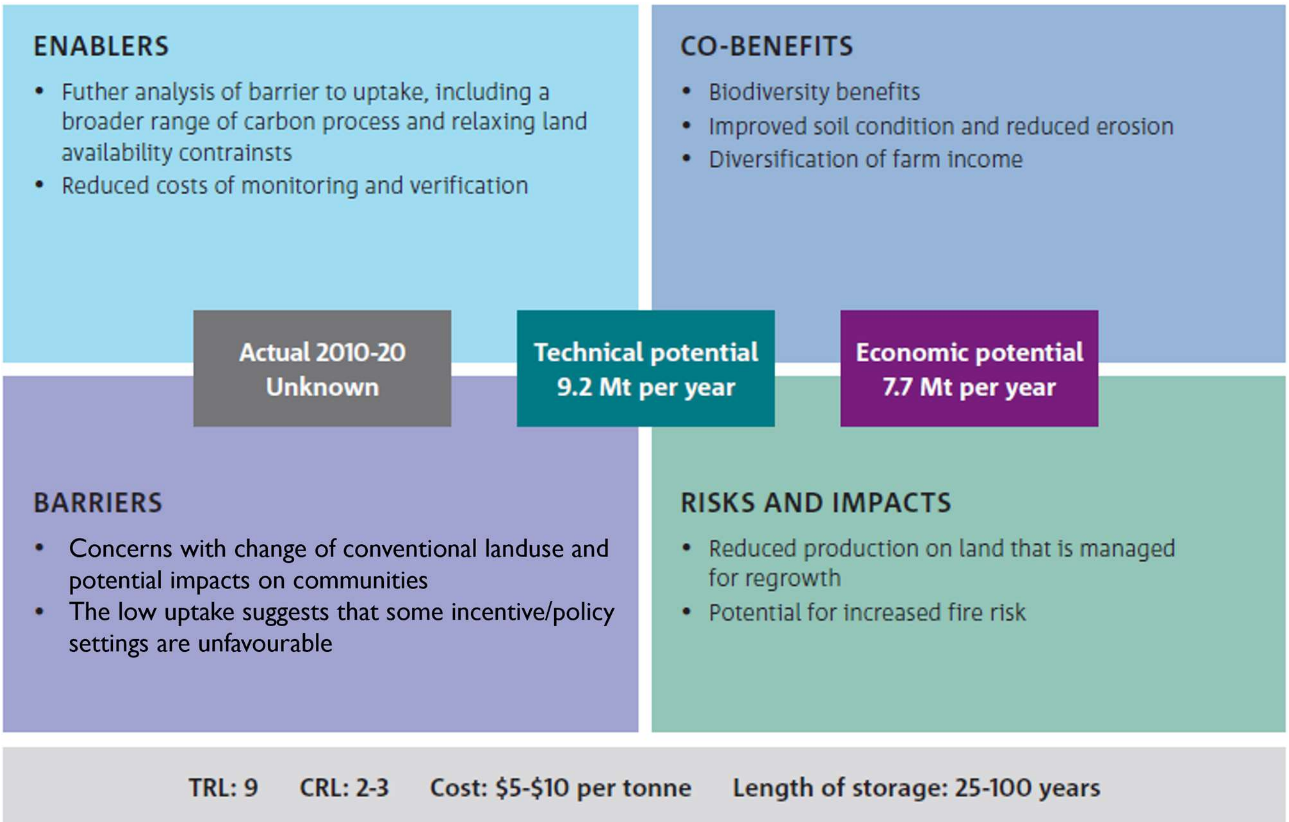



**Figure 7-1: Summary of Avoided Clearing. Actual sequestration for avoided clearing is not readily available from the AGEIS database, due to difficulties in identifying land areas where deliberate decisions were made to cease clearing activity. To provide some broader context, average annual re-clearing rate of previously cleared forested land (2010-2020) were 358,200 ha $yr^{-1}$.**

## 7.2 Description and current uptake

Avoided land clearing recognises sequestration from retaining areas of native vegetation that would otherwise have been cleared as part of 'business as usual' management activities. Sequestration can either be based on preventing existing 'mature' vegetation from being cleared, or the cessation of repeated clearing of vegetation that is in the process of recovering from a past clearing event(s). A key component of the activity is therefore demonstrating that the vegetation would, indeed, have been cleared during the normal course of events. This proof could be in the form of a sustained historical record of repeated clearing, or documented proof of intent to clear, for example through possession of a valid land clearing permit. Whilst it is plausible that there are soil carbon benefits to avoided land clearing, a lack of empirical evidence prevents this pool currently being included in any accounting frameworks. There is, however, clear evidence for positive carbon benefits associated with the protection of living biomass, and debris.

In theory, Avoided Clearing could be applied to any vegetation that is planned to be cleared, such as shrublands or other non-forest ecosystems. In practice, and as implemented in the ERF, the activity is limited to avoided land clearing of forested vegetation. Assessing the potential eligible area where a valid land clearing activity could take place is more challenging than other activities, due to additional criteria associated with tenure and intended future land management, over and above biophysical considerations. To partially address this, the analysis of existing ERF methods forms the basis of the sequestration estimates reported here. In particular, the *Avoided Clearing of Native Regrowth* (2015) methodology provides a set of criteria associated with evidential proof for past clearing activity, and establishing legal rights to undertake the clearing, that would likely be common criteria for broader implementation of this activity.

In addition to the *Avoided Clearing of Native Regrowth (2015)* methodology, there is also the *Avoided Deforestation (2015)* methodology, that also address avoided clearing. Although both methodologies seek to reward the same basic sequestration mechanism, the eligibility requirements for each, and method of sequestration calculation, differ.

The *Avoided Clearing of Native Regrowth* methodology has had relatively limited uptake, amounting to just 0.2% of the total ERF contract portfolio. Sequestration under the method is calculated using FullCAM. The key requirement is a need to provide evidence of the two most recent clearing events. There is also a requirement to demonstrate that the vegetation satisfies the requirements of forest cover, that the forest comprises native species, that there is an unrestricted right to clear the land, and that following clearing the forest regenerates. There is also a requirement that each Carbon Estimation Area (CEA) within a project shares the same management history. This latter requirement was not able to be verified in the analysis of technical sequestration described below, due to the scale at which the clearing data were available, although it is recognised that this constraint could, in practice, significantly reduce the sequestration potential. The analyses below should therefore be interpreted as the maximum potential under the method, in the absence of the requirement to demonstrate uniformity in management at the scale of individual CEAs.

In contrast the *Avoided Deforestation* method has seen more widespread uptake, amounting to 12.2% of the total ERF contract portfolio. The key eligibility requirement for the *Avoided Deforestation* methodology is the possession of a valid clearing consent that was issued before 1 July 2010, for the purposes of permanent conversion of forest cover to cropland or grassland. In effect, this limited the scope of the activity to properties in NSW that had permits to clear vegetation through an Invasive Native Scrub Property Vegetation Plan (INS PVP), issued prior to 2010 under the New South Wales Native Vegetation Act 2003 (repealed 2017). Analysis of the remaining unrelinquished permits indicates some potential for new project activity (up to 5 Mt $CO_2$-e $yr^{-1}$; Roxburgh et al. 2020a), however it is likely that these remaining permits have not been relinquished for reasons external to the assumptions in that analysis, and Roxburgh et al. (2020a) concluded future sequestration under this methodology is likely negligible. For these reasons it is not considered further, with the analysis below based only on *Avoided Clearing*.

To provide some broader context to land clearing activity in Australia, over the period 2010-2020 the average annual area of secondary land clearing (i.e., re-clearing of land that had been cleared at least once previously) was 358,200 ha $yr^{-1}$. This is approximately 26% of the total potential land area identified in the Sequestration Potential section below (land clearing data from Australia's National Greenhouse Gas Inventory[19], with values extracted from the AGEIS online database[20]).

## 7.3 Sequestration potential

| Estimate of sequestration | Sequestration ($Mt.yr^{-1}$) | Key evidence |
|---|---|---|
| **Technical Potential** | 9.2 | Based on spatial modelling to identify potential areas for future activity, and FullCAM simulations to calculate sequestration potential (Roxburgh et al. 2020a). |
| **Economic potential by 2025** | NA | |
| **Economic potential by 2035** | NA | |
| **Economic potential by 2050**[1] | 7.7 | Based on discounted cash flow modelling of the technical sequestration results, with an assumed carbon price of \$30 t $CO_2$-e, and a discount rate of 10% (Roxburgh et al. 2020a). |

[1]The economic sequestration calculation did not consider the possible time course of delivery, nor the staggering of new projects over time, hence no time course of ACCU delivery is provided. The economic sequestration value represents the maximum sequestration achievable assuming all new potential projects could be established over the near term (e.g., the next 1-2 years).

**Table 7-2: Best estimate of Avoided Land Clearing sequestration potential**

### 7.3.1 Technical sequestration

A key input to the calculation of the technical sequestration extent is knowledge of the land areas that are currently forest, but that have been cleared at least twice in the past. This information was provided by the Department of Industry, Science, Energy and Resources (DISER, now DCCEEW) at the scale of SA2 regions (ABS 2011), from the national greenhouse gas National Inventory System (NIS) spatial database. The economic potential extent was therefore defined by the SA2 regional extent, with only the total area of available land within each region known (and not the exact location). A further assumption was that avoided clearing activity will occur in areas of grazed native vegetation (GNV) (ABARES 2017). Within each SA2 the area of land that is currently forested but has been subject to two prior clearing events (area 'A') was compared to the area of GNV (area 'B'). When area 'A' exceeded area 'B' the total eligible area was taken to be 'Area 'B'. Conversely, if area 'B' exceeded area 'A', then the total eligible area was taken to be area 'A'.

To include the requirement that there must be an unrestricted right to clear the land, further filtering was required. For Queensland, only the subset of the potential area that comprised Category 'X' vegetation was retained for analysis. For the Northern Territory, the potential area comprised existing land clearing permit extents (available at https://nrmaps.nt.gov.au/nrmaps.html). For the remaining states and territories, it was assumed that land with forest that was greater than 20 years of age was ineligible. The current age of the forest was also provided by DISER, from the NIS spatial database.

[19] National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

[20] Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

Technical sequestration for each SA2 region was calculated using the FullCAM tree yield formula with expansion factors (to obtain root biomass and debris from above-ground biomass) calculated from the continental-scale spatial library of spatial $Block_{LMG}$ simulations described in the natural regeneration of native forest chapter.

Because the precise spatial locations of the economic potential areas within each SA2 were unknown, a single representative FullCAM simulation for each SA2 was run, using the mean maximum above-ground biomass parameter within the grazed native vegetation extent within each SA2, and using the $Block_{LMG}$ growth parameters. A baseline clearing interval of 15 years was assumed and subtracted from the project simulation assuming no clearing. Through this analysis, the total eligible area was 1.382 Mha, with a potential average annual sequestration 9.21 Mt $CO_2$-e $yr^{-1}$. (Figure 7-2).

**Table 7-3:** Technical sequestration associated with the Avoided Clearing of native Regrowth methodology for the area identified in Figure 1.

| Planting type | 25yr sequestration (Mt $CO_2$ e) | 25yr annual average (Mt $CO_2$ e $yr^{1}$) | Area (MHa) |
|---|---|---|---|
| **Avoided Clearing of Native regrowth** | 230.13 | 9.21 | 1.382 |

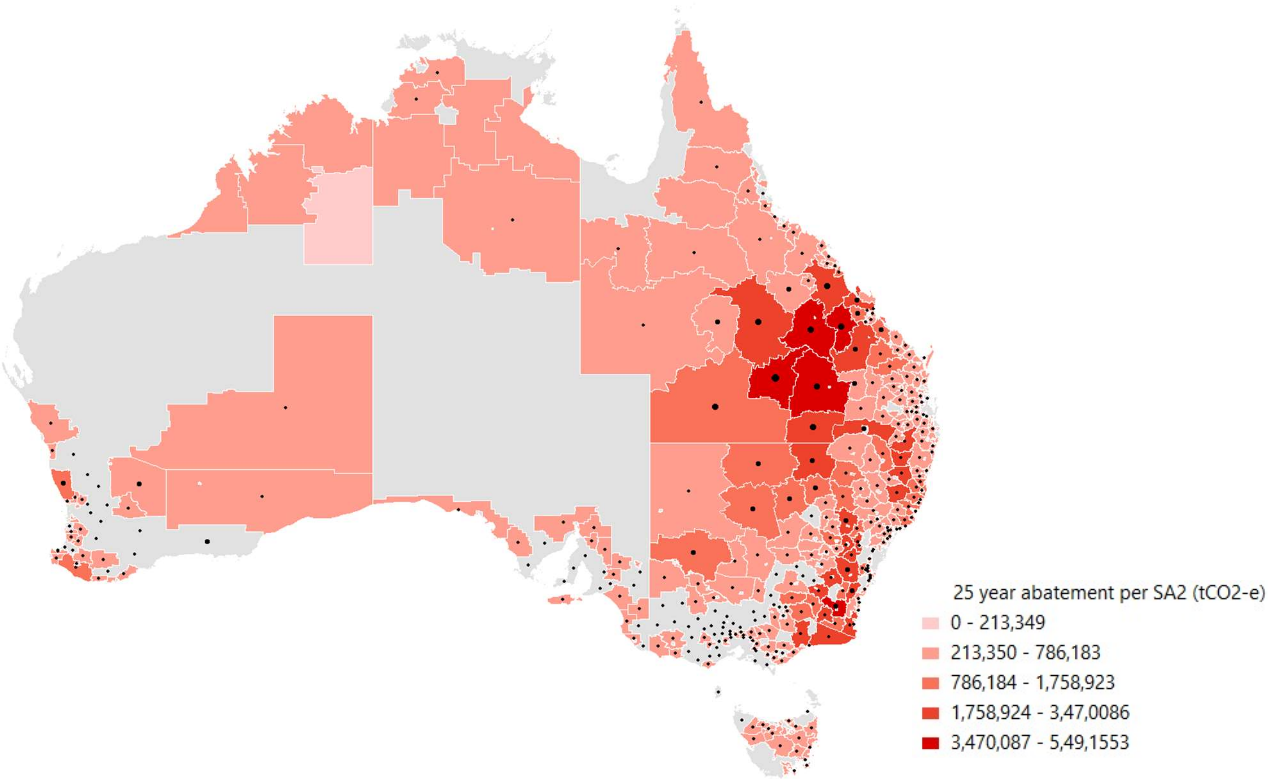



**Figure 7-2:** Statistical local area's (SA2s) economic potential for Avoided clearing, based on a 15 year baseline assumption, \$144 $ha^{-1}$ clearing costs and initial costs of \$10 $ha^{-1}$, and a carbon price of \$30 t $CO_2$-$e^{-1}$. Red SA2 regions are those that contain economic potential areas, and the black symbols are proportional to the total available area within each region.

### 7.3.2 Economic sequestration

As per the analysis in the Natural Regeneration of Native Forest section, the total potential area comprised a number of small, isolated patches of eligible land that were deemed unlikely to be large enough to support a viable project. Therefore, areas of land that were less than 25 ha in extent and that were greater than 50km from the nearest eligible patch of land greater than 25 ha were excluded from the economic analysis. This resulted in a reduction in the economic potential area from 1.382 Mha to 1.239 Mha.

Consistent with prior work (Eady et al. 2009) economic filters in addition to the adjustment for project area were applied to limit the technical sequestration areas to the economic potential subset. The assessment of economic viability included both the direct and the opportunity costs of undertaking activities (including lost income from reduced cattle grazing potential), which are compared against the expected revenues. Discounted cash flow modelling was applied, whereby locations were flagged as being likely to transition to carbon farming if the net present value (NPV) of the carbon farming activity exceeded current profitability. Full details of the economic modelling are provided in Roxburgh et al. (2020a). Because the economic sequestration is sensitive to the assumed carbon price, minimum and maximum values are presented, corresponding to carbon prices of \$15 t $CO_2$-e and \$30 t $CO_2$-e, respectively. For reporting in Figure 7.2, the sequestration associated with the \$30 t $CO_2$-e carbon price was used.

| Planting type | 25yr sequestration (Mt $CO_2$ e) | 25yr annual average (Mt $CO_2$ e yr $^{1}$) | Area (MHa) |
|---|---|---|---|
| **Avoided Clearing of Native regrowth** | 178.25 - 193.52 | 7.13 - 7.74 | 1.10 - 1.18 |

**Table 7-4: Economic sequestration associated with the Avoided Clearing methodology. The ranges reflect two carbon price assumptions, \$15 t $CO_2$-e (lower bound) and \$30 t $CO_2$-e (upper bound).**

## 7.4 Technology Readiness Potential and Commercial Readiness

### 7.4.1 Technology Readiness

| Technology readiness | \$ per tonne $CO_2$e | Key Evidence |
|---|---|---|
| 9 | ~5-10 | Only direct costs of undertaking activities are included in the price, comprising project transactions costs (assumed to be 25% of achieved sequestration), and establishment costs (\$10 ha$^{-1}$). |

**Table 7-5: Avoided Land Clearing Technology Readiness Level**

**Explanation:**

The basis of the sequestration calculation is very similar to that for Natural Regeneration of Native Forest, except rather than account for accumulated sequestration over time, avoided losses of existing vegetation are estimated. The tools for undertaking such accounting are well established and are similar to other activities associated with vegetation management, thus there are few technological barriers.

### 7.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| 2-3 | The low number of projects under this methodology suggest some settings are unfavourable to widespread roll out at this stage, particularly given the favourable cost per tonne of sequestration. |

Table 7-6: Avoided Land Clearing Commercial Readiness Level

**Explanation:**

The low number of ERF projects under this methodology suggest certain settings are not favourable to widespread roll out at this stage. Consideration of the rules associated with the methodology suggest three possible reasons. One is the evidentiary requirements to document at least two past clearing events, which may prove a barrier if one or more clearing events was undertaken prior to the availability of suitable aerial or remote sensing records. A second is the requirement to demonstrate the vegetation satisfies forest cover, precluding inclusion of managing non-forest woody vegetation. The third is the requirement that each Carbon Estimation Area (CEA) within a project shares the same management history, which would require detailed spatial records of past management activity to identify and demarcate homogenous areas. This latter constraint was not included in the estimates reported here.

Comparison of current (2010-2020) rates of secondary clearing (358.2 kha $yr^{-1}$, Section 7.2 ) are similar to previous decades (1990-2010), with an average 377.1 kha $yr^{-1}$. This may suggest some reliability in the availability of land on which to undertake Avoided Land Clearing activity into the future, although future availability could be sensitive to changes in land clearing legislation.

## 7.5 Scalability, Length of storage, Measurement and Verification

### 7.5.1 Scalability

The difference between what is possible and what has economic potential is less for this activity than other methods involving the management of vegetation, with approximately 80% of the technical sequestration deemed to be economic. The reasons for the low take up thus far therefore deserve further scrutiny. Additionally, broadening the definition of eligible land beyond forests could expand the potential area available, and the technical sequestration.

### 7.5.2 Length of storage.

Because the avoided land clearing activity involves the protection of existing vegetation, the question of risks to accumulation are less relevant, particularly where past regeneration was based on vegetative recovery rather than seedbanks, thus avoiding the vulnerable seedling stage of regeneration. Given the requirement for the vegetation to be pre-existing, this suggests the most vulnerable regrowth stages would already have been successfully navigated. Although less relevant, risks to accumulation in areas that have been more recently cleared will be higher, with susceptibility to climatic extremeness (droughts, heatwaves, frost), and fire disturbance. The main risks associated with sequestration permanence include mortality associated with extreme drought, and rates of post-drought recovery. In the areas most suited to the Avoided Clearing methodology the fire risk is relatively higher than the natural regeneration of native forest activity, due to higher productivity and greater contiguity of ground fuels (Roxburgh et al. 2020b).

### 7.5.3 Measurement and Verification

Because the activity involves avoiding the loss of current vegetation, the sequestration is readily visible from both the ground and from space. Sequestration can therefore either be measured directly via field measurement or can be indirectly estimated via modelling based on remotely sensed data, or via terrestrial carbon models calibrated specifically for quantifying carbon in recovering vegetation, such as FullCAM (Paul and Roxburgh 2020). Field measurements across large spatial scales are logistically prohibitive, particularly given the high spatial variability of biomass characteristic of these environments, therefore measurement-informed modelling is both a robust and practical alternative. There is potential to improve current tools for measurement, reporting and verification (MRV), for example the development of methods based on satellite imagery to provide continental-scale consistency in the detection of changes in vegetation cover, which could also potentially be extended to include non-forested woody vegetation.

## 7.6 Social, environmental impacts, risks and co-benefits

### 7.6.1 Social impacts and risks

The main social impacts of implementing the activity are related to reduced production (primarily beef) on the lands that are managed for regrowth, and associated impacts on local communities that have been historically based on rangeland production rather than carbon farming. However, the scale of the potential identified here (in the order of 1-2 Mha continentally) suggests such effects might be limited, or localised.

### 7.6.2 Environmental impacts and risks

The environmental impacts of retaining and increasing native forest cover are likely to be mostly positive, associated with habitat restoration and biodiversity recovery. There may be additional impacts associated with subsequent changes to the proportion of overstory (trees and shrubs) and understory (predominantly grasses) vegetation, with possible implications for accessibility, ground cover, surface erosion, and runoff. There are also potential fire risks associated with increased vegetation cover, although changes in the balance between surface and elevated fuels makes generalisation difficult. These potential impacts require further attention.

### 7.6.3 Co-benefits

Similar to promoting the Natural Regeneration of Native Forests, and in addition to diversification of farm incomes, the primary co-benefits associated with Avoided Land Clearing involve ecosystem restoration, particularly the recovery of habitat for both flora and fauna. Most of the identified opportunity involves the management of Category 'X' vegetation in Queensland (Figure 7.3). Given this vegetation type includes 'endangered' or 'of concern' Brigalow ecosystems, the biodiversity gains and potentially significant.

## 7.7 Barriers to implementation:

### 7.7.1 Policy and regulatory environment

The economic favourability of avoided clearing arises from moderate rates of per ha sequestration (averaging 6.6 t $CO_2$-e $ha^{-1}$ $yr^{-1}$) combined with low upfront costs and model-based sequestration estimates that avoid costs associated with field-based measurement. These results raise the question as to why this methodology has had low participation thus far – and given the moderate to high technical sequestration identified, this deserves closer attention. One possible reason is high beef and property prices, where a carbon price in excess of \$30 t $CO_2$-e may still be insufficient for carbon farming to be considered an economically viable land use. Also, as noted in Section 7.4.2, it is possible the requirements to provide documented evidence for past clearing events, to demonstrate subsequent regeneration, to demonstrate an unrestricted right to clear the land, and the requirement that all CEAs share the same management history, have together proved to be a barrier to adoption. Easing some of these restrictions could extend the area of applicability and total technical sequestration.

Recent claims questioning the additionality of sequestration under the Avoided Deforestation methodology (Macintosh et al. 2022) highlight the complexities of defining and establishing rules that involve both regulatory (based on providing external proof of clearing intent) as well as biophysical considerations for identifying eligible areas for activity.

In response, the Australian Government has commissioned an independent expert panel to review the integrity of Australian Carbon Credit Units (ACCUs) under the Emissions Reduction Fund. The Review will consider whether particular methods subject to recent claims continue to comply with the scheme's integrity standards.

### 7.7.2 Social licence and stakeholder acceptance

The Avoided Land Clearing activity is the converse of the Natural Regeneration of Native Forests activity, in that rather than promoting native forest regeneration, the activity is focused on preventing vegetation loss to start with. Therefore, social licence and stakeholder acceptance might be expected to be similar, with general acceptance but with some concerns over changes to traditional land management. One differentiating factor between the two activities is that the Avoided Land Clearing activity is likely to occur in higher rainfall, more productive regions, which may involve different social considerations given the potential for differences in farming practices.

### 7.7.3 Technology performance variability

Variability in technology performance is unlikely to be a barrier to implementation for Avoided Land Clearing activities, given the transparent and clear evidence of successful sequestration that can be directly observed, and the sound basis and high confidence on which the main technological intervention (ceasing land clearing) is known to protect carbon stores that would otherwise have been lost to the atmosphere.

### 7.7.4 Financial proposition and costs and access to capital

Avoided Land Clearing has relatively low start-up costs, with additional savings in removing the costs of future clearing. Taken together, the economic analysis indicated general economic favourability for this activity.

### 7.7.5 Industry supply chains and skills

From a technological perspective, Avoided Land Clearing is a relatively straightforward and easy to implement solution, not requiring investment in complex machinery, nor specialist skills training to facilitate project implementation. Industry supply chains and skills are therefore unlikely to provide significant barriers to implementation.

### 7.7.6 Market opportunities or market creation

Avoided land Clearing is already supported by the ERF and its associated market mechanism, with ACCUs purchased either directly by government, or traded on the open market. The early success and rapid uptake of the Avoided Deforestation ERF methodology demonstrated the viability of the activity under the right settings (although see Section 7.7.1 regarding questions over additionality). The economic analyses undertaken here show, in general, strong potential for increased participation in this activity. Further analysis is required to better understand the current barriers.

## 7.8 Scaling knowledge gaps:

Scaling knowledge gaps include:

1. Expansion of the analyses presented in this section to include a broader range of carbon prices and land eligibility, beyond those that are consistent within the constraints of the ERF framework.
2. Exploration of the potential to extend avoided clearing activity to include non-forested woody vegetation.
3. Exploration of relaxing some of the assumptions underlying the current analysis, including relaxing the requirement for existing vegetation to meet the forest cover definition to include all woody vegetation more broadly; relaxing the proof requirements to demonstrate at least two past clearing events; and the requirement to stratify projects into homogenous land management units. Avoided emissions from the displacement of grazing cattle could also be included as part of a revised feasibility analysis, although understanding how much of that reduced grazing pressure would simply be shifted elsewhere (leakage) is an open question.
4. Further analysis of the current barriers to participation, given the economic viability and sequestration potential identified (up to approximately 8 Mt $CO_2$-e $ha^{-1}$ $yr^{-1}$ ).

## 7.9 Chapter References


ABARES. (2017) Land use of Australia 2010-11. https://data.gov.au/dataset/ds-dga-bba36c52-d5cc-4bd4-ac47-f37693a001f6/details.

ABS. (2011). Australian Statistical Geography Standard (ASGS): Volume 1 - Main Structure and Greater Capital City Statistical Areas, July 2011, cat. no. 1270.0.55.001, Canberra.

Eady, S. et al. (2009) *An Analysis of Greenhouse gas Mitigation Opportunities from Rural Land Use*. CSIRO.

Macintosh, A., Butler, D., Ansell, D., Waschka, M. (2022). The Emissions Reduction Fund (ERF): Problems and Solutions. https://law.anu.edu.au/sites/all/files/erf_-_problems_and_solutions_final_6_april_2022.pdf.

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020a) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, p. 425.

Roxburgh Stephen H., Paul K. & Pinkard E. (2020b) Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF). Report for the Climate Change Authority. p. 224.

# 8 Savanna Fire Management

| Emission Type | Avoided | Negative |
|---|---|---|
| Enabling Capture Technology | Biological | Engineered |
| Enabling Storage Technology | Biological | Engineered |

**Table 8-1: Savanna fire management technology type**

## 8.1 Summary

**Description and current uptake**

Savanna fire management (or savanna burning) involves increasing the prevalence of cooler, early dry season fires with the intention of reducing large, high intensity, late dry season fires, based on the assumption that seasonality (fire timing) is sufficient to capture broad patterns of fire intensity. This land management practice has two potential pathways for abatement: reducing greenhouse gas (GHG) emissions (emissions avoidance) from the late dry season fires, and increasing carbon being sequestered in dead organic matter and living vegetation (sequestration). Only the sequestration component is included in this chapter.

Analyses reported here are based on existing ERF methodologies, which limit the sequestration component to detached (on-ground) dead organic matter. It has been proposed the new savanna fire management methodology, that is currently under development[21], will additionally include standing dead organic matter and sequestration in live biomass, and will also extend the spatial extent of eligible activity area to include a new vegetation fuel class, Pindan. Soil carbon sequestration is excluded, given incomplete understanding of changes in soil carbon following savanna fire management.

In practice, savanna burning activities are restricted to areas with frequent fire (with fire return intervals from approximately every 7 years up to every 1–2 years). In Australia, current savanna burning activities are restricted to two rainfall zones in northern Australia: 600–1,000 mm annual rainfall, and >1,000 mm annual rainfall (where most of the current activity occurs).

Results from Australia's annual national greenhouse gas accounting report current sequestration of 5.6 Mt $CO_2$-e $yr^{-1}$ averaged over the years 2016-2020, which includes living biomass, debris and soil carbon.

**Sequestration potential**

Potential land area for savanna burning projects includes land covered by eligible vegetation fuel types within each of the two rainfall zones. The identified area of technical sequestration was identified to be more than 80 Mha, with a total technical sequestration of 6.19 Mt carbon dioxide equivalents ($CO_2$-e) per year (25-year annual average). At a carbon price of $30 t $CO_2$-e, all the technical sequestration was deemed to be economic (6.19 Mt per year) at a cost of $5 per tonne.

---

[21] https://www.cleanenergyregulator.gov.au/ERF/Pages/Method%20development%20tracker/Method-development-tracker.aspx#Savanna-fire-management

**Technology readiness potential and commercial readiness**

Savanna burning sequestration estimation protocols are well established and based on extensive scientific study. Abatement based on emissions avoidance is well established in the market, with several commercial providers already demonstrating commercial readiness. However, despite the potential for significant sequestration and seeming financial favourability, there has been limited interest in adding sequestration. This may be due to a reluctance to commit to permanent sequestration activities (involving maintaining the activity for the next 25–100 years).

**Scalability, length of storage, measurement and verification**

There are currently more savanna burning emissions avoidance projects under the ERF in the high rainfall zone compared to the low rainfall zone. This suggests a role for factors outside of the modelling assumptions, such as lower biomass (and hence lower sequestration potential) in more arid areas, and less reliable fire return intervals.

Sequestration projects, requiring ongoing maintenance of fire management to maintain benefits, face risks such as persistent water stress leading to a decline in maximum biomass potential and lower technical sequestration, and changes in the timing of current fire regimes resulting from climate change.

**Social, environmental impacts, risks and co-benefits**

There have been significant positive social impacts associated with the introduction of savanna burning across northern Australia, including employment opportunities and associated support for Indigenous communities. In addition, there are significant positive environmental impacts, including increased ground cover, reduced mortality of flora and fauna, reduction in the spread of invasive Gamba Grass, and the protection of fire-sensitive ecosystems. However, there are situations where intense, late fires might be a necessary management tool and removing them from the landscape could be detrimental.

Savanna fire management has wide range of co-benefits, in addition to carbon sequestration. Biodiversity outcomes have the potential to include increased protection of vulnerable biodiversity, with additional benefits from reducing soil erosion and stream sediment transport. Savanna burning projects have also led to enhanced engagement with local Indigenous communities and individuals, improved employment prospects in regional northern Australia, and expanded the institutional capacity of local management organisations.

Unlike other sequestration activities, such as reforestation where once trees are established the sequestration is self-sustaining, long-term storage under savanna fire management requires ongoing application of the fire management treatment. A significant risk to sequestration is therefore cessation of fire management through changes in land management, leading to the reversal of any sequestration gains.

There are also risks to sequestration associated with increases in temperature, that are projected to be most extreme in the regions where savanna fire management projects occur. Increasing temperatures have the potential to impact plant growth, and hence rates of sequestration. Savanna regions are also impacted by cyclones, and these are projected to intensify. Increasingly extreme bushfire weather through increasing temperatures, VPD and other climatic drivers poses an additional risk to storage, whereby changing fire regimes, with overall increases in fire severity, have the potential to negate fire management interventions.

**Barriers to implementation**

Recent changes to the savanna burning methodology (to allow sequestration as well as emissions avoidance) have not led to uptake of sequestration options. Given the changes, it appears barriers to adoption of sequestration activities may not be limitations in the regulatory or policy framework but may be social (such as limiting future land management options due to the permanent nature of sequestration activities). Recognition of the many co-benefits associated with the technology confers a broad social license and stakeholder acceptance.

Implementation of savanna burning projects can require significant technological input. Spatial analysis and GIS skills are needed to develop project extents and mapping. Expertise is required to identify eligible vegetation types across the landscape. Advanced aerial technologies may be needed, such as automated delivery of incendiary devices from aircraft.

Savanna burning is already supported by the ERF and its associated market mechanism. Successful savanna burning sequestration projects have demonstrated the viability of the activity, given the right settings.

**Scaling knowledge gaps**

Further investigation is needed into the current barriers for participation in savanna emissions avoidance and sequestration activities. This includes looking into social, policy and project implementation issues. Extension of the analyses to include sequestration in standing dead material and living biomass, and extension into new regions, is required to generalise the results presented here. Extending methods based on remote sensing to quantify fire severity, in addition to area burnt, could provide greater temporal resolution, and increase the accuracy of savanna fire management activity measurement and verification.

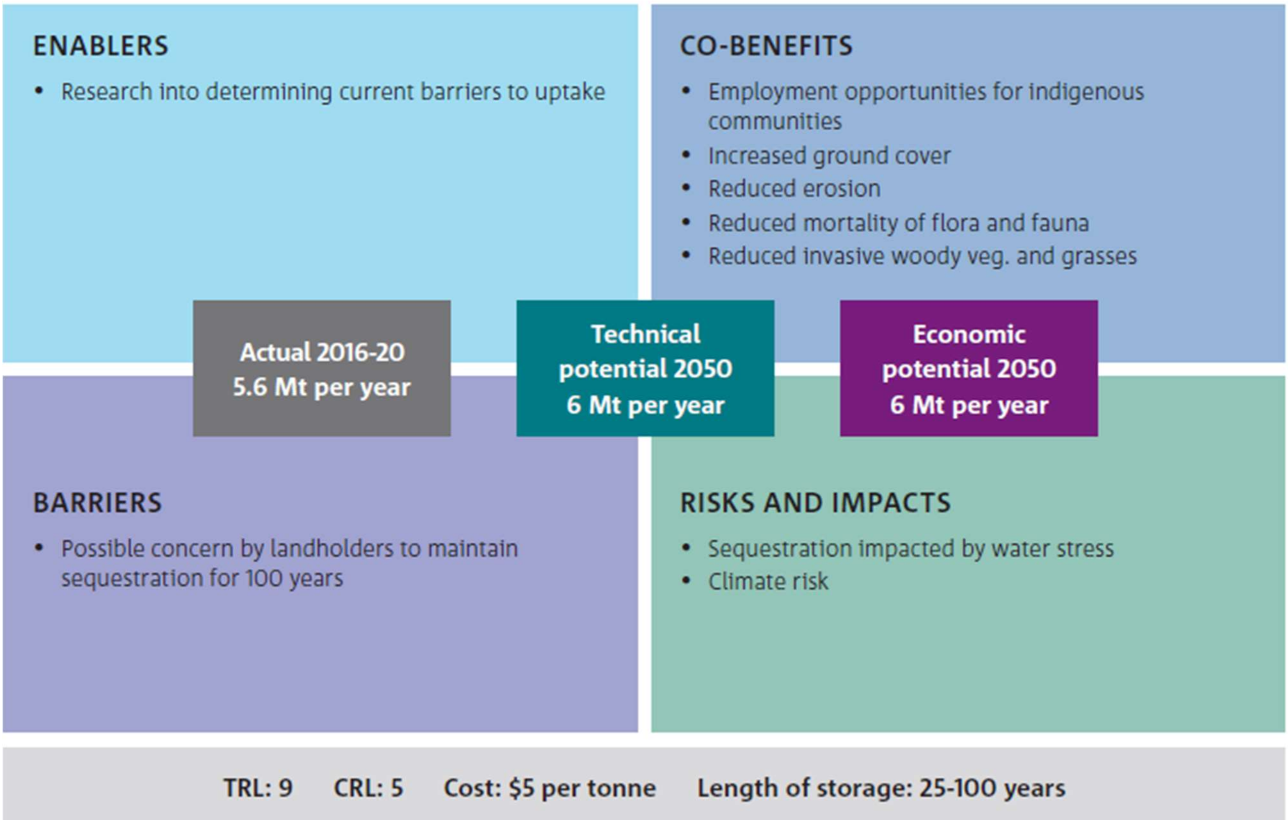



**Figure 8-1: Summary of Savanna fire management. Actual sequestration reflects sequestration in living biomass, debris and soil organic carbon for savanna regions in Australia, averaged over the period 2016-2020, as reported in Australia's annual national greenhouse gas inventory. Note that potential and economic sequestration includes only detached (on-ground) debris.**

## 8.2 Description and current uptake

Under savanna fire management, strategic burning is carried out with the intention of reducing large high intensity late dry season fires through increasing the prevalence of cooler early dry season fires. The underlying assumption is that seasonality (fire timing) is sufficient to capture broad patterns of fire intensity, notwithstanding the potential for some late-season fires, under certain circumstances, to burn at low intensity (Yibarbuk et al. 2001), and *vice versa*. This management change reduces overall greenhouse gas emissions (methane and nitrous oxide), and results in an increase in carbon being sequestered in dead organic matter and living biomass. Planned burning occurs primarily in the early dry season and may include igniting fires from aircraft, from vehicles along the sides of roads and tracks, from boats on waterways, or by walking across country. Other fire management activities include burning firebreaks to prevent the spread of unplanned fire or undertaking fire suppression in the late dry season. The specific type and timing of fire management depends upon landscape features within the project area and local weather conditions. There are two potential sources of abatement. The first is emissions avoidance, whereby abatement occurs through reductions in the non-$CO_2$ greenhouse gases methane and nitrous oxide. The second source of abatement is the resulting increase in sequestration in dead organic matter and living biomass. Only the sequestration component of sequestration is considered in this chapter.

In practice, savanna burning activities are restricted to areas with frequent fire (with fire return intervals from approximately every 7 years up to every 1-2 years). This is to provide adequate historical data on which to calculate baseline (i.e., pre-project) emissions. Current Savanna burning activities are restricted to two rainfall zones in northern Australia: 600mm to 1000mm annual rainfall, and >1000mm annual rainfall. Most of the current activity occurs within the >1000mm rainfall zone.

Results reported in Roxburgh et. al. (2020a) were used to provide estimates of sequestration associated with savanna fire management. Because the analyses in that report were specific to sequestration that could be achieved under current relevant ERF methodologies, they should be considered a conservative assessment of sequestration that could be achieved more generally. Additional lands that were excluded from that analysis, but which could also be managed to increase carbon stores, include areas below the 600mm rainfall contour (although though fuel loads and fire return intervals become increasingly limiting as aridity increases). Additionally, the sequestration estimates only include the detached (on-ground) dead biomass pools, as it has only been relatively recently that sufficient evidence to quantify the likely magnitude of sequestration achievable in living biomass in response to fire management has emerged. It is proposed the new savanna fire management methodology, currently under development[22], will additionally include standing dead organic matter and sequestration in live biomass, and will also extend the spatial extent of eligible activity area to include a new vegetation fuel class, Pindan. The results summarised below also exclude changes in soil carbon, given the high-level of uncertainty associated with changes in soil carbon following savanna burning management.

The ERF has methodologies that cover both emissions avoidance, and emissions avoidance and sequestration. The corresponding current methods are *Savanna Fire Management Emissions Avoidance* (2018) and *Savanna Fire Management Sequestration and Emissions Avoidance* (2018). The results below are consistent with the sequestration component of the second of these methodologies.

[22] https://www.cleanenergyregulator.gov.au/ERF/Pages/Method%20development%20tracker/Method-development-tracker.aspx#Savanna-fire-management

To provide some broader context for sequestration under savanna fire management, results from Australia's National Greenhouse Gas Inventory[23], with values extracted from the AGEIS online database[24], indicate an average annual sequestration (2016-2020) of 5.6 Mt $CO_2$-e $yr^{-1}$, which includes living biomass, debris, and soil organic carbon. The 2016 – 2020 averaging period includes the impacts of extensive savanna burning projects under the ERF.

## 8.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt.yr 1) | Key evidence |
|---|---|---|
| **Technical Potential** | 6.19 | Based on modelling to identify potential areas for future activity, and SavBAT simulations combined with analysis of existing project performance to calculate sequestration potential (Roxburgh et al. 2020a). |
| **Economic potential by 2025** | NA | |
| **Economic potential by 2035** | NA | |
| **Economic potential by 2050[1]** | 6.19 | Based on discounted cash flow modelling of the technical sequestration results, with an assumed carbon price of \$30 t $CO_2$-e, and a discount rate of 10% (Roxburgh et al. 2020a). |

[1]The economic sequestration calculation did not consider the possible time course of delivery, nor the staggering of new projects over time, hence no time course of ACCU delivery is provided. The economic sequestration value represents the maximum sequestration achievable assuming all new potential projects could be established over the near term (e.g., the next 1-2 years). Under the assumptions of the economic modelling, all technical sequestration is viable at a price of \$30 t CO2-e.

**Table 8-2: Best estimate of Savanna fire management sequestration potential**

### 8.3.1 Technical sequestration

#### Technical sequestration extent

The total extent of eligible area for savanna burning projects includes the land area covered by eligible vegetation fuel types, within each of the two rainfall zones (Table 8-4). Whilst projects must develop and validate their own vegetation mapping for project purposes, for the analyses here the default vegetation mapping available at https://v3.savbat.environment.gov.au/img/vegfuelbase_a.tiff was used. This map provides a distribution of each of the eligible vegetation types, at a 250 m x 250 m resolution.

Two potential extents were identified. One for the establishment of new projects outside of the existing project boundaries, with abatement from sequestration calculated, and secondly, the extension of existing avoidance projects to include sequestration. Revoked ERF projects that had not received any credits were considered eligible for future projects. The potential extent for new project establishment was further reduced through the removal of the Gamba Grass exclusion zone, which is specified in the current ERF methodology as being ineligible for savanna burning activity, given the high flammability of this species and risks for adverse consequences. The total eligible area for new project establishment is 55.78 Mha, and the total eligible area of existing projects is 24.77 Mha (Figure 8-2).

---

[23] National Inventory Report Volume 2. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-2.pdf

[24] Department of Climate Change, Energy, the Environment and Water. 2022. Australian Greenhouse Emissions Information System (AGEIS). https://ageis.climatechange.gov.au/ - accessed 22/08/2022.

Table 8.3. Eligible vegetation fuel types for Savanna Burning projects.

| Rainfall zone | Vegetation fuel code | Description |
|---|---|---|
| High | hOFM | Open Forest with Mixed grasses (Tussock and Hummock) |
| | hWMi | Woodland with Mixed grasses (Tussock and Hummock) |
| | hWHu | Woodland with Hummock grass |
| | hSHH | Shrubland (Heath) with Hummock grass |
| Low | lWHu | Woodland with Hummock grass |
| | lWMi | Woodland with Mixed grasses (Tussock and Hummock) |
| | lWTu | Woodland with Tussock grass) |
| | lOWM | Open Woodland, with Mixed grasses (Tussock and Hummock) |
| | lSHH | Shrubland (Heath) with Hummock grass |

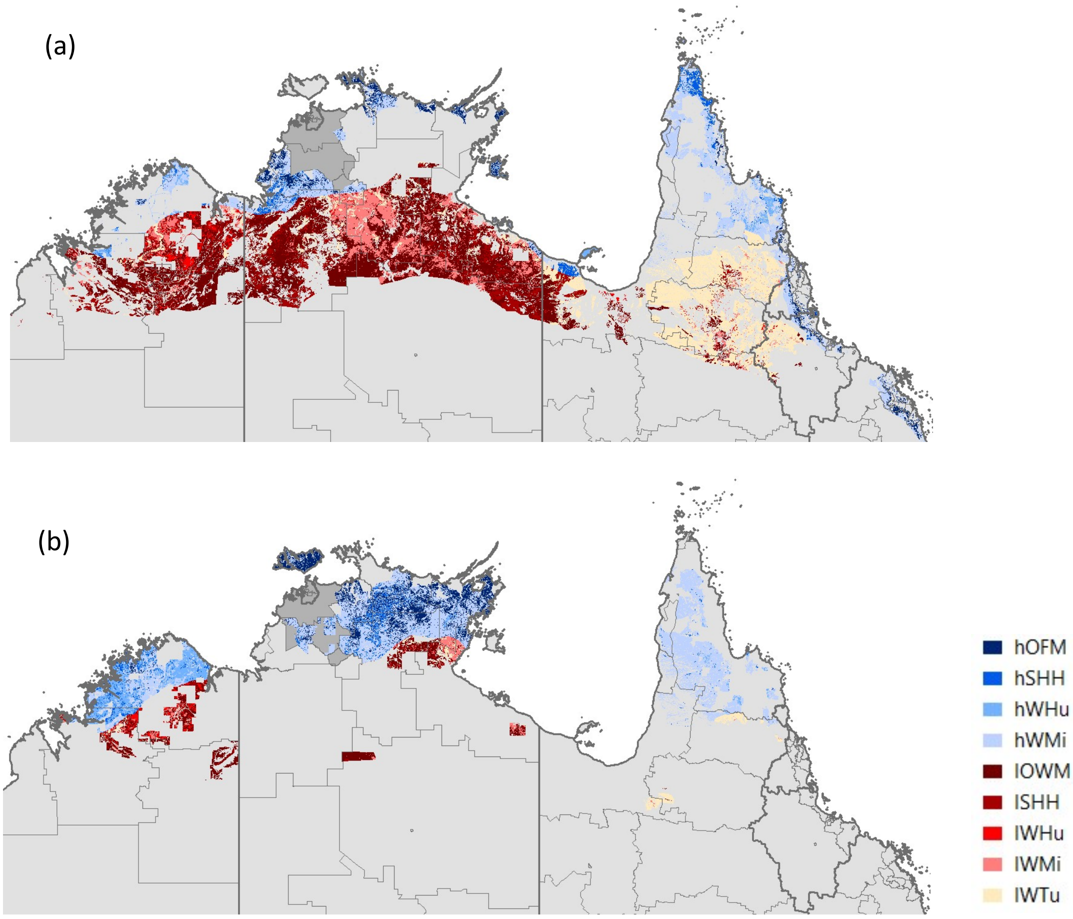



Figure 8-2:(a) Potential area for new savanna burning projects. (b) potential area defined by existing ERF savanna burning sequestration projects that could additionally include sequestration. Darker grey area is the Gamba exclusion zone. Statistical local area 4 (SA4) Regions are demarcated by thick grey lines; Statistical local area 2 (SA2) Regions are demarcated by thin grey lines.

### Technical sequestration

*Spatial representation*

The technical sequestration for new projects (i.e., excluding current project areas) was based on predicted baseline emissions using SavBAT 3.0[25], using the baseline period 2008-2018. Analysis by SavBAT requires uploading GIS layers defining the analysis extent and the spatial distribution of each eligible vegetation fuel type. To obtain baseline emissions that are broadly spatially representative, the potential areas in Figure 8-2 were disaggregated into SA4 statistical areas, and each SA4 area was uploaded and analysed using SavBAT and the baseline emissions recorded. To provide a slightly finer regional resolution for the economic analyses these SA4-level baseline emissions were then statistically down-scaled to the SA2 level (retaining the separation of the different vegetation fuel classes) through proportionally allocating the total emissions to each SA2 area.

*Calculation of technical sequestration for new projects*

Cook et al. (2016) reported that, over a 25-year crediting period, average sequestration in the open forests vegetation type (hOFM) was expected to be 6.87 t $CO_2$-e $ha^{-1}$, or 0.27 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ annualised. For the woodland vegetation types the expected sequestration is 4.77 t $CO_2$-e $ha^{-1}$, or 0.20 t $CO_2$-e $ha^{-1}$ $yr^{-1}$. Cook et al. (2016) further noted that an expansion factor (to convert emission avoidance to sequestration) was approximately 3.7, i.e., for every tonne of $CO_2$-e avoided 3.7 tonnes is expected to be sequestered. In an alternative calculation, based on the WALFA project (Russell-Smith et al. 2013) the avoidance sequestration is 0.045 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ which corresponds to expansion factors of 0.27/0.045 = 6.0x for open forests and 0.20/0.045 = 4.4x for woodlands.

These expansion factors (derived independently of the ERF methodology calculations) are, however, based on emissions accounting methods that in general give lower emissions avoidance than the 2015 methodology determination on which the majority of available project data is based. Repeating the calculation utilising the same data on which the avoidance calculations were based (Figure 4.7.2 in Roxburgh et al. 2020a) yields an average per ha emissions avoidance of 0.09 t $CO_2$-e $ha^{-1}$ $yr^{-1}$, and corresponding expansion factors of 2.99 and 2.08 for open forests and woodlands, respectively. Because the available data on which the emissions avoidance was calculated was predominantly obtained from calculations under the 2015 methodology, these expansion factors were therefore used as the basis for calculating the sequestration component, whereby sequestration was calculated as either 2.99 x emissions avoidance, or 2.08 x emissions avoidance, for open forests and woodlands respectively. No sequestration was calculated for the non-forest hSHH and lSHH vegetation fuel types.

*Calculation of technical sequestration for existing projects*

The same factors developed in the previous section to expand avoidance emissions in new project areas to sequestration were applied to the existing project areas. However, because SavBAT could not be used to generate the baseline emissions for current projects (as the results would have been confounded by the on-ground fire management activities), the per ha emissions avoidance for new project areas was used to calculate emissions avoidance for existing projects, through multiplying by the existing project areas.

The total predicted technical sequestration and associated areas are summarised in Table 8-3. Because the sequestration is independent across these scenarios, the total technical sequestration is given as the sum across all scenarios: 6.19 Mt $CO_2$-e $yr^{-1}$.

[25] https://savbat.environment.gov.au/

**Table 8-3:** Summary of technical sequestration areas and total technical sequestration for savanna fire management (sequestration).

| Activity area | 25yr sequestration (Mt $CO_2$ e) | 25yr annual average (Mt $CO_2$ e yr [1]) | Area (MHa) |
|---|---|---|---|
| New projects | 87.7 | 3.51 | 55.8 |
| Existing projects | 67.1 | 2.68 | 24.8 |
| **Totals** | 154.8 | 6.19 | |

## 8.3.2 Economic sequestration

Economic sequestration was based on an assessment of economic viability, where both the direct and the opportunity costs of undertaking activities were compared against the expected revenues. Discounted cash flow modelling was applied, whereby the SA2 regions that provided the spatial context for the technical sequestration calculations were flagged as being likely to transition to carbon farming if the net present value (NPV) of the carbon farming activity exceeded current profitability. An annual cost of 60 cents per hectare was based on the following, with full details of the economic modelling and assumptions given in Roxburgh et al. (2020a):

- In 2011 the WA Department of Environment and Conservation advised that it used a cost of 15 cents per hectare for the planning and delivery of prescribed fires in Kimberley country (Sparrow et al. 2011). Of the properties analysed by Sparrow et al. (2011), one was found to face a similar cost per hectare (Warrigundu, 324,000 hectares), while another had a significantly higher cost of 43 cents per hectare (Merepah, 186,000 hectares). This higher cost was mainly due to the assumption that an additional permanent worker would be hired, whereas the Department's cost assumed seasonal labour would be used. Given the hiring practices of individual projects is unknown, the average of these two estimates was used: 30 cents per hectare.
- The above properties are on the larger side, so benefit from economies of scale. To account for the likely smaller sizes of properties involved in ERF fire management projects, the per hectare cost was inflated to 40 cents. Further, to account for 10 years of inflation since the analysis by Sparrow et al. (2011), the per hectare cost was increased to 45 cents.
- Start-up costs of $50,000 and reporting costs of $10,000 per year were assumed. Based on a 25 year crediting period and a discount rate of 10%, the start-up costs translate to an equivalent annual cost of $5,500 per year. Therefore, the start-up and reporting costs are $15,500 per year. This converts to a cost of about 10 cents per hectare under the assumption that the average property size is about 150,000 hectares. This gives a final total annual cost of 55 cents per hectare.
- It was assumed that projects incur an additional annual cost of 5 cents per hectare. This reflects an additional cost of $7,500 per year to cover additional reporting requirements, along with weed monitoring and removal.

Results from this analysis showed most of the sequestration volume becomes viable at carbon prices of $1-15. A key assumption in this analysis is that there are limited barriers to uptake when including sequestration in a project. It is likely that proponent concerns, such as the requirement to pay back sequestration ACCUs generated in the case of project revocation, are perceived as significant risks to undertaking the activity. Although such additional constraints were out of scope for this analysis, they are nevertheless likely very important for the utilisation of the savanna sequestration option, and such proponent perceptions deserve closer scrutiny. Because the economic sequestration is sensitive to the assumed carbon price, minimum and maximum values are presented, corresponding to carbon prices of \$15 t $CO_2$-e and \$30 t $CO_2$-e, respectively. Summary values provided in Table 8-1 assume a carbon price of \$30 t $CO_2$-e.

| Activity area | 25yr sequestration ($Mt\ CO_2\ e$) | 25yr annual average ($Mt\ CO_2\ e\ yr^{1}$) | Area (MHa) |
|---|---|---|---|
| New projects | 85.9 – 87.7 | 3.44 – 3.51 | 52.9– 55.6 |
| Existing projects | 67.1 – 67.1 | 2.68 – 2.68 | 24.8 – 24.8 |
| **Total** | 153.0 – 154.8 | 6.12 – 6.19 | |

**Table 8-4: Economic sequestration associated with the implementation of savanna fire management. The ranges reflect two carbon price assumptions, \$15 t $CO_2$-e (lower bound) and \$30 t $CO_2$-e (upper bound).**

## 8.4 Technology Readiness Potential and Commercial Readiness

### 8.4.1 Technology Readiness

| Technology readiness level | \$ per tonne $CO_2$e | Key Evidence |
|---|---|---|
| 9 | ~5 | Only direct costs of undertaking activities are included in the price, totally \$0.60 $ha^{-1}$ (Section 8-3-2) |

**Table 8-5: Savanna fire management Technology Readiness Level**

**Explanation:**

Savanna burning sequestration estimation protocols, including the use of the SavBAT tool to facilitate sequestration calculations, are already well established. The basis of the technology is based on extensive scientific study.

### 8.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| 5 | Sequestration under savanna fire management is already included in the current ERF methodology, and is being extended under the new proposed ERF methodology. |

**Table 8-6: Savanna fire management Commercial Readiness Level**

**Explanation:**

The limited interest in adding sequestration, despite the potential for significant sequestration and seeming financial favourability, suggest some settings are unfavourable to widespread roll out at this stage. This may be a result of reluctance to commit to permanent sequestration activities, involving committing to maintaining the activity for the next 25 (or 100) years, as opposed to avoidance, where landholders can choose to opt out at any time without penalty.

## 8.5 Scalability, Length of storage, Measurement and Verification

### 8.5.1 Scalability

Savanna fire management is already occurring at scale (approximately 25Mha. Table 8-2; Figure 8-3b), and although the focus across those areas is emissions avoidance, sequestration benefits are being accrued as well, albeit not formally recognised as part of reported abatement. The economic analysis indicated little or no difference between what is possible and what is economic. The reasons for the low take up thus far therefore deserve further scrutiny. Regarding sequestration, potential barriers associated with committing to a permanence period for project activity were discussed in the commercial readiness section above. The current predominance of avoidance projects in the high rainfall zone (>1000mm annual rainfall) and relative lack of expansion into the low rainfall zone (600 – 1000mm annual rainfall) suggest a role for factors outside of the assumptions on which the modelling was based are important. This could include lower biomass (and hence lower sequestration) in the low rainfall zone, with less reliable fire return intervals.

### 8.5.2 Length of storage

Unlike other sequestration activities, such as reforestation where once trees are established the sequestration is self-sustaining, long-term storage under savanna fire management requires ongoing application of the fire management treatment. A significant risk to sequestration is therefore the cessation of fire management through changes in land management, leading to the reversal of any sequestration gains.

The biggest climatic risk to sequestration identified by Roxburgh et al. (2020a) for savanna burning projects was a persistent increase in water stress leading to a decline in maximum biomass potential, and thus, a potential decline in sequestration.

Of all the regions in Australia, the increases in temperature are projected to be the highest in the regions where savanna fire management projects occur. It is also a region that experiences cyclones, and these are projected to intensify. Increasingly extreme bushfire weather is an additional risk to storage, whereby changing fire regimes through increasing temperature, VPD and other climatic drivers has the potential to negate fire management interventions. Control of gamba grass is a key risk mitigation strategy in those areas under threat from this invasive species.

### 8.5.3 Measurement and Verification

Savanna burning measurement and verification protocols, including the use of the SavBAT tool to facilitate sequestration calculations, are already well established and widely used. Extensive scientific study of both emissions from fires of different intensities, and dynamics of dead organic matter, have been used to inform these protocols. Opportunities to improve measurement and verification include refining methods based on remote sensing to quantify fire severity (i.e., the amount of biomass consumed) in addition to area burnt. This could potentially allow fire management to be applied without the requirement to specify (somewhat arbitrary) dates to define early dry season, and late dry season fires.

## 8.6 Social, environmental impacts, risks and co-benefits

### 8.6.1 Social impacts and risks

There have been significant social impacts associated with the introduction of Savanna Burning across northern Australia, particularly through the development of employment opportunities and associated support for indigenous communities (Russell-Smith et al. 2015).

### 8.6.2 Environmental impacts and risks

The whole premise of the Savanna Burning activity is to generate significant environmental impact, through replacing intensive and damaging late-season fires with cooler, less damaging early season fires. These impacts include increased ground cover and hence potential for reduced erosion, reduced mortality of flora and fauna, and protection of fire-sensitive ecosystems. One potential exception are situations where intense, later fires might be a necessary management tool, and removing them from the landscape could be detrimental. For example, to control woody thickening and encroachment which impacts pastoral production or conservation values, and the management of high biomass flammable exotic grass species (Gamba Grass). There may also be potential health risks associated with savanna fire management, with Jones et al. (2022) demonstrating an increase in smoke pollution and decline in air quality following the expansion of savanna fire management over the period 2004 and 2019.

### 8.6.3 Co-benefits

Savanna burning projects have an extensive history of delivering a wide range of co-benefits, particularly with respect to indigenous livelihoods and biodiversity outcomes. Through reducing high intensity later season fire, vulnerable biodiversity can be protected, soil erosion and stream sediment transport can be reduced, and also with a reduction in airborne particulates (although see Section 8.6.2 above). Regarding biodiversity benefits, Corey et al. (2020) have noted that there is a strong basis to expect positive biodiversity outcomes, but further confirmatory evidence is required. The authors also warned of potential biodiversity dis-benefits, and that, overall, improved monitoring programs are required to better understand how the spatial and temporal arrangement of fires influences biodiversity, and interactions with other threatening processes.

Institutionally, savanna burning projects have led to enhanced engagement with local indigenous communities and individuals, improved employment prospects in regional northern Australia, and increased the institutional capacity of local management organisations (Russell-Smith et al. 2015). Broader cultural outcomes, such as the passing down of indigenous fire management knowledge through generations, including broader ecosystem management knowledge associated with fire management, is also a feature of this activity. The Indigenous Ranger Program[26] has also been instrumental in supporting various ‘caring for country’ activities, through funding employment opportunities for Aboriginal and Torres Strait Islander Australians in land management, including support of savanna fire management activities and associated environmental and social co-benefits. In general, carbon credits from savanna burning activities are also highly regarded by corporate purchasers, given the broad range of co-benefits that they provide.

---

[26] https://www.niaa.gov.au/indigenous-affairs/environment/indigenous-ranger-programs

## 8.7 Barriers to implementation:

### 8.7.1 Policy and regulatory environment

Recent changes to the Savanna Burning methodology to allow sequestration as well as emissions avoidance have not yet led to enhanced uptake of the sequestration option, despite the potential for increased sequestration and the financial favourability. The barriers to adoption therefore would not seem to be limitations of the current policy or regulatory environment, given relatively little extra effort is required in the way of measurement or verification to include sequestration as well as emissions avoidance in projects. The primary barriers may be social, associated with a reluctance of landholders to commit to a 25 (or 100) year permanence period. This requires further investigation.

### 8.7.2 Social licence and stakeholder acceptance

Savanna Burning activities have broad social licence and stakeholder acceptance, driven by the many recognised co-benefits associated with reducing wildfire emissions. In part, this may be due to the remote locations in which these activities take place. This has been facilitated by the synergy between achieving greenhouse gas outcomes and other environmental and social benefits, and through the establishment of networks such as the Indigenous Carbon Industry Network[27],

### 8.7.3 Technology performance variability

Savanna Burning projects are likely more reliable in the higher rainfall regions, with higher biomass, higher fuel loads, and more regular fires. This may explain the relative slow uptake of savanna projects in the lower rainfall zone. Also, as rainfall declines fuel loads also decline, and fires become less frequent. Given the limited timeframe of the remote sensing record (post-1988), this has implications for being able to detect sufficient fire cycles with which to establish robust emission and sequestration baseline conditions.

### 8.7.4 Financial proposition and costs and access to capital

Overall, the economic analysis indicated strong economic favourability for this activity.

### 8.7.5 Industry supply chains and skills

Implementation of Savanna Burning projects can involve significant technology, including spatial analysis and GIS skills to develop project extents and mapping, vegetation expertise to inform and identify eligible vegetation types across the landscape, and (optionally, as early burning treatments can be implemented manually on the ground) advanced aerial technologies, such as automated delivery of incendiary devices from aircraft. These skills are well developed, to service current demand.

### 8.7.6 Market opportunities or market creation

Savanna Burning is already supported by the ERF and its associated market mechanism, with ACCUs purchased either directly by government, or traded on the open market. The success of savanna burning sequestration projects demonstrates the viability of the activity under the right settings. The economic

---

[27] https://www.icin.org.au/

analyses undertaken here show, in general, strong potential for increased participation in this activity. Further analysis is required to better understand the current barriers.

## 8.8 Scaling knowledge gaps:

Scaling knowledge gaps include:

- Investigation into the current barriers for participation in savanna sequestration activities, which would include social, policy and project implementation issues, including any barriers associated with permanency and obligations to maintain fire management into the future.
- Exploration of expanding savanna fire management beyond the ERF-based analyses presented here, to include potential expansion beyond the current 600mm lower rainfall limit, and inclusion of the impacts on living biomass.
- Re-analysis of the results presented here to include additional sequestration in standing dead material, and living biomass; and extension to the newly proposed Pindan vegetation fuel category.
- Explore opportunities to improve methods based on remote sensing to quantify fire severity, in addition to area burnt, and to improve delineation of burnt and unburnt patches. This could potentially allow fire management to be applied without the requirement to specify (somewhat arbitrary) dates to define early dry season, and late dry season fires.

## 8.9 Chapter References


Cook, G.D., Meyer, C.P., Muepu, M. & Liedloff, A.C. (2016) Dead organic matter and the dynamics of carbon and greenhouse gas emissions in frequently burnt savannas. International Journal of Wildland Fire 25, 1252-1263.

Corey B., Andersen A. N., Legge S., Woinarski J. C. Z., Radford I. J. & Perry J. J. (2020) Better biodiversity accounting is needed to prevent bioperversity and maximize co-benefits from savanna burning. Conservation Letters 13, e12685.

Jones P. J., Furlaud J. M., Williamson G. J., Johnston F. H. & Bowman D. M. J. S. (2022) Smoke pollution must be part of the savanna fire management equation: A case study from Darwin, Australia. Ambio 51, 2214-26.

Russell-Smith J., Cook G. D., Cooke P. M., Edwards A. C., Lendrum M., Meyer C. P. & Whitehead P. J. (2013) Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. Frontiers in Ecology and the Environment 11, e55-e63.Eady, S. et al. (2009) *An Analysis of Greenhouse gas Mitigation Opportunities from Rural Land Use*. CSIRO.

Russell-Smith J., Yates C. P., Edwards A. C., Whitehead P. J., Murphy B. P. & Lawes M. J. (2015) Deriving Multiple Benefits from Carbon Market-Based Savanna Fire Management: An Australian Example. PLOS ONE 10, e0143426.

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020a) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, p. 425.

Roxburgh Stephen H., Paul K. & Pinkard E. (2020b) Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF). Report for the Climate Change Authority. p. 224.

Sparrow A., Cook G., Chewings V., Reeson A., Andersen A. & McKaige B. (2011) Scope for Carbon Farming Through Savanna Burning on the Indigenous Land Corporation's Northern Cattle Properties.' (Indigenous Land Corporation: Adelaide, SA.).

Yibarbuk D., Whitehead P. J., Russell-Smith J., Jackson D., Godjuwa C., Fisher A., Cooke P., Choquenot D. & Bowman D. M. J. S. (2001) Fire ecology and Aboriginal land management in central Arnhem Land, northern Australia: a tradition of ecosystem management. Journal of Biogeography 28, 325-43.


.

# 9 Soil Carbon

| | | |
|---|---|---|
| **Emission Type** | Avoided | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

Table 9-1: Soil carbon technology type

## 9.1 Summary

**Description and current uptake**

Soil carbon sequestration is based on managing land to keep carbon in the soil. This is done through practices that increase the rate at which carbon is accumulated into the soil (such as improving plant cover and retaining stubble), decrease the rate at which carbon is lost from the soil (such as reducing rates of decomposition and minimising erosion losses), or changing the nature of the material added to the soil so that it lasts longer.

Over time and management changes, soils become saturated and reach a new equilibrium in their ability to sequester carbon. The biggest changes in soil carbon occur early after introducing new management practices and a given strategy will not necessarily result in a constant rate of soil carbon change. For soil carbon sequestration to be effective, land managers may need to maintain practices that retain the balance between inputs and outputs. Accordingly, any ongoing emissions associated with continued practice change need to be considered when deploying soil carbon sequestration as eventually carbon stocks in the soil will saturate but emissions associated with practices to maintain these stocks will be on going.

The current uptake of soil carbon technology in Australia includes 15 projects contracted with Australia's Emissions Reduction Fund (ERF) and 324 non-contracted projects. Instigation and baselining of projects is rapidly increasing with potentially 500,000ha of new area baselined in 2024.

The Australia's National Greenhouse Gas Inventory reports average annual average emissions in the two categories cropland and grassland soils across Australia's, over the period 2010-2020, of 4.8 Mt $CO_2$-e $yr^{-1}$.

**Sequestration potential**

Technical sequestration from applying different management practices is estimated to be 115 $Mt.yr^{-1}$. Economic sequestration potential estimates (25-year average, broadly based on a costs methodology) from applying different management practices range is estimated to be between 5 to 29 $Mt.yr^{-1}$ at a cost of between $7 to $13 per tonne.

**Technology readiness potential and commercial readiness**

The management approaches used to increase soil carbon are well established (such as decreasing grazing pressure or converting cropland to annual pasture). The costs for changing activities range from $7 per t $CO_2$-e for low yielding projects to $13 per t $CO_2$-e for high yielding projects, however the cost of implementing practice change and opportunity cost of these changed practice can influence this markedly.

Commercial projects are being established in niche areas, and there is some emerging competition between project providers.

**Scalability, length of storage, measurement, and verification**

Soil carbon sequestration in some cases has a positive return because it can increase productivity and provide other on-farm benefits. It can be scaled up through three broad approaches: a direct subsidy to limit practices that decrease soil carbon, payments to sequester soil carbon, and market or value chain mechanisms that reward practices that build soil carbon.

Land management changes leading to increased soil carbon are not a permanent sequestration of any soil carbon molecule. Evidence suggests that if the practices that increased soil carbon are stopped and prior practices are resumed, soil carbon stocks will revert to the pre-intervention level. Practices that lead to increase in soil carbon in more long-lived pools such as charcoal and humus provide more security of sequestration.

Soil carbon can be measured through direct measurement, proximal and remote sensing, and modelling. These approaches are not mutually exclusive. Some level of direct measurement is likely to be required to support any estimate of carbon sequestration (even if only to provide the starting point for modelling).

**Social, environmental impacts, risks, and co-benefits**

Using soil for carbon sequestration may reduce future management options and can lock up macro nutrients, such as nitrogen and phosphorus. There is a drying trend associated with climate change in some parts of Australia, and this is impacting net primary production. A meta-analysis of climate change effects on soil carbon found both positive and negative interactions with climate factors and concluded that there was a moderate to high risk of loss of soil carbon stocks from climate change.

Increased soil carbon is associated with a range of productivity and environmental benefits including improvements to soil structure, soil fertility, nutrient retention, water holding capacity and reduced soil erosion. Co-benefits of increased soil carbon include sustaining and improving productivity, reducing the need for fertiliser inputs, and reducing the impacts of drought and dust storms.

**Barriers to implementation**

Soil carbon methods are well supported by the existing policy and regulatory environment; however, industry proponents have claimed that monitoring, reporting and verification (MRV) costs are significant barriers to entry. Due to the well documented co-benefits, soil carbon projects are perceived as positive by stakeholders. While the sector is well served by advisers and implementation partners, farmers and land managers are often unclear as to the suitability of the advice they are given by project proponents.

Traditional chemical approaches to measuring soil carbon are challenging and require soil samples to be collected, transported from the field to a laboratory and carefully processed under standardised conditions. Emerging proximal and remote sensing techniques may replace some of the more laborious steps of the process and markedly reduce measurement costs.

**Scaling knowledge gaps**

There is currently a significant focus on reducing measurement costs associated with validating soil carbon changes. Gaps in knowledge beyond this include uncertainties in the economic sequestration potential of the technology due to competition between methods and reliable data on longer term intervention outcomes and how microbiome management could increase soil carbon. Some of these questions might be addressed by modelling of potential soil carbon change under emerging agricultural practices and the vulnerability of soil carbon stocks.

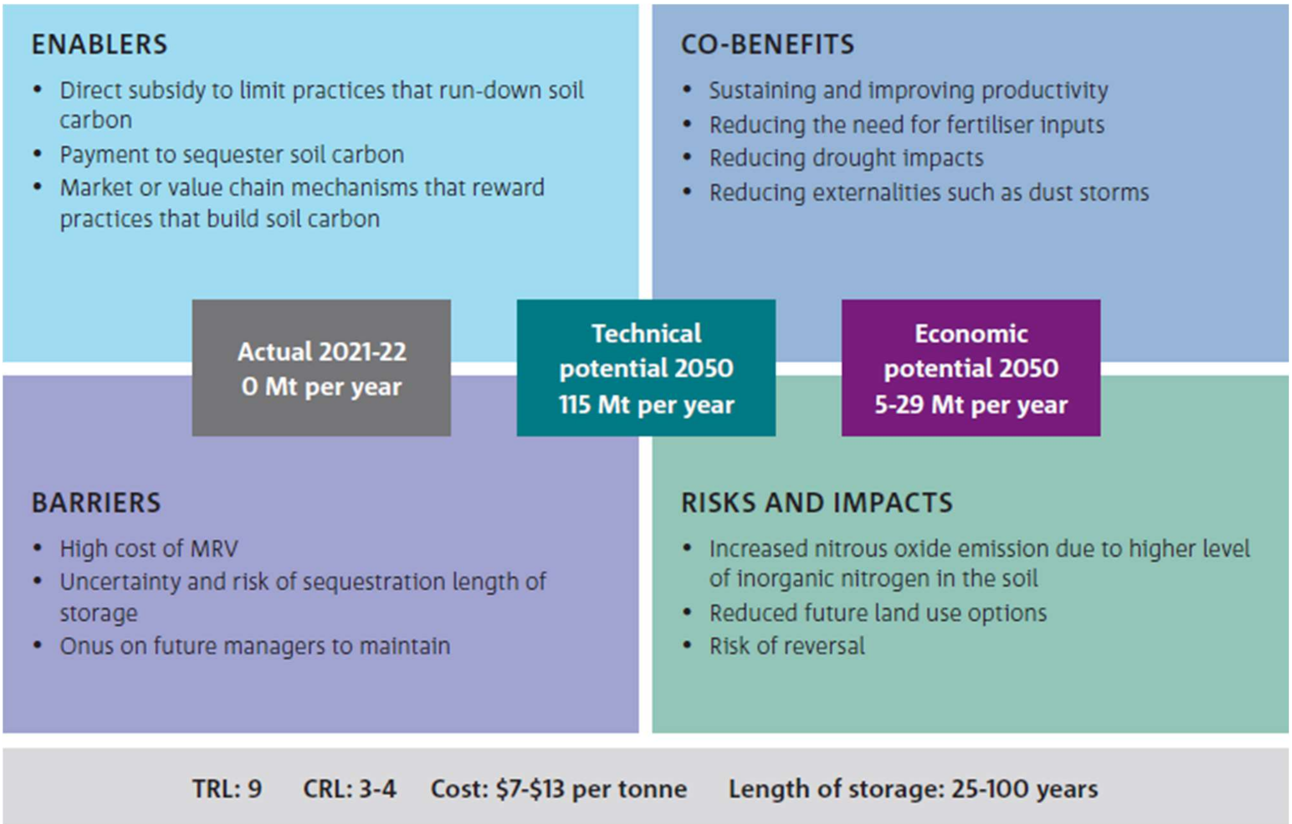



**Figure 9-1: Summary of enablers, co-benefits and risks and impacts of soil carbon technology. Actual estimate is from ERF project register of issued ACCU's accessed July 2022.**

## 9.2 Description and current uptake

For the sake of this review soil carbon we provide some definitions. Total soil carbon is carbon within the soil in all its forms and includes both soil organic matter and inorganic carbon as carbonate minerals that is less than 2mm in diameter. Soil organic carbon is the total carbon in soils derived from biological sources that is less than 2mm in diameter. Soil organic matter is used to describe the mixture of materials including particulate organics, humus and charcoal along with living microbial biomass and fine plant roots found in soil that is less than 2mm in diameter. The focus of this report is soil organic carbon.

The basis of soil carbon sequestration is a change in land management that either increases the rate at which carbon is accumulated into the soil or decreases the rate at which soil carbon is lost from the soil, or both. As a result soil carbon can be increased by one of three ways: increasing input rate of carbon (processes such as improving plant growth or cover which increase inputs via photosynthesis, reducing removal rates of vegetation inputs through such processes as stubble retention), decreasing losses (reducing rates of decomposition through such processes as minimal tillage or minimising erosion losses) or increasing the residence time of carbon in the soil carbon pool primarily through stabilisation processes which protect organic matter from decomposition e.g. binding to clays, protection within soil aggregates, and to a lesser extent, increased chemical recalcitrance of C inputs (Lehman and Kleber 2015). Soil carbon storage locally can also be increased if we add additional material such as organic amendments or biochar, although a full lifecycle assessment should be undertaken to account for where this material was sourced and emissions in its generation (and also to ensure we haven't simply moved carbon from one part of the landscape to another).

Conversion of land with native vegetation to agriculture has typically reduced soil organic carbon stocks in the order of 20-60% from pre-clearing levels (Sanderman et al. 2010, Luo et al. 2010). The Australia's

National Greenhouse Gas Inventory reports average annual average emissions in the two categories cropland and grassland soils across Australia's, over the period 2010-2020, of 4.8 Mt $CO_2$-e $yr^{-1}$. Changes in practice that increase carbon inputs (for example through increased crop productivity, or decreased export of organic matter) into soil and/or decrease losses (say through reduced soil erosion or slowed decomposition of organic matter additions to soil) should increase soil organic stocks, especially in soils that have lost carbon post clearing. In some instances, carbon stocks may be increased relative to native vegetation due to the imposition of management that alleviates a plant growth constraint (e.g., irrigation or fertilisation), though typically such increases would be vulnerable to subsequent loss.

It is generally assumed that soils have a finite capacity to sequester carbon: over time they become saturated and reach a new equilibrium relative to the input and output regimes. The upper threshold of soil carbon will be determined by soil and landscape attributes such as soil depth, soil texture, soil physical properties such as aggregation and the constraining factors on plant production such as nutrient deficiency and pH. Plant species, or crop choice, influence the rooting depth and therefore the depth to which soil carbon change is likely to occur. Climate also affects soil organic carbon stocks by affecting plant growth and the rate of microbial decomposition.

Following a change in management practice or climate the subsequent change in inputs and outputs will lead soil to shift to a new equilibrium so long as the conditions and practices remain constant. These changes in soil carbon can take long periods of time to equilibrate with more than 50 years of constant management required to reach new equilibrium values (Smith 2005). The biggest changes in soil carbon induced by management change are noted early after the change in management occurs. It is not correct to assume that a given management strategy will result in a constant rate of soil carbon change through time. This may appear to occur in the first years after management change, but the size of any annual change will decrease through time.

Use of soil as a sequestration option will place an onus on future managers of that land to maintain practices to retain carbon stocks. This will reduce future land management options and can be a disincentive because permanence is required for soil sequestration options to be effective. Where a strong alignment between increasing soil carbon and improving or restoring farm productivity or resilience exists, this is not the same issue and potentially offers a win:win provided risks can be managed.

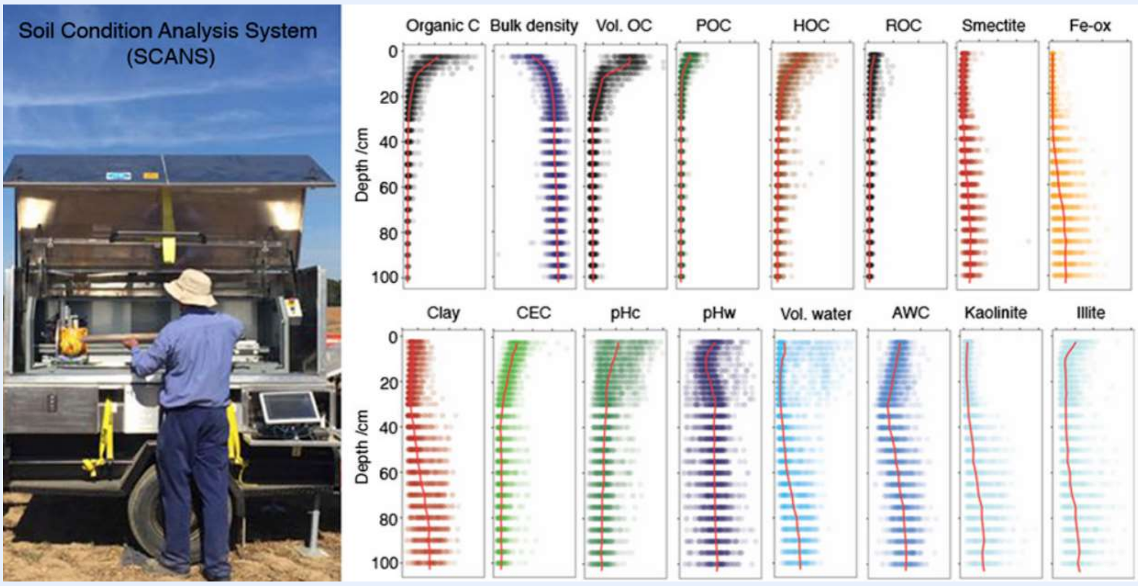
Sustaining soil carbon requires net primary production to be maintained. In some parts of Australia there is a drying trend associated with climate change and projections, and in Australia net primary productivity is strongly correlated with rainfall posing a threat to soil carbon. Declining rainfall is already impacting potential crop productivity and will continue to do so into the future (Hochman et al 2017), though to date technology improvement has prevented loss of production despite a 20-30% decrease in the theoretical water-limited yield (Hochman et al. 2017; Fletcher et al. 2020). This may be exacerbated by drives to increase the harvest index of crops, increasing allocation of carbon to grains and thus reducing the amount that remains as stubble or root inputs to soil.

Sequestering carbon also locks up macro nutrients such as nitrogen, sulphur, and phosphorus due to the stoichiometry of soil organic matter, which affects long-term costs of increasing soil carbon (Kirkby et al. 2013). However, it is important to note that past productivity may in part be due to the release of these nutrients from soil organic matter that has been lost over time – commonly referred to as nutrient mining.

Finally, because practices that increase soil carbon need to be maintained over the long run to maintain soil carbon increases, it is important to look at net emissions over integration periods relevant to atmospheric outcomes. Luo et al. (2017) showed that for fertiliser addition to crops, while systems acted as sink for the first few years, over the longer term some systems can become net emissions sources. The balance of carbon-to-nutrients (stoichiometry) is an important driver of both soil carbon sequestration and risk of N2O emissions. The changes in the rate of soil carbon accumulation over time and the ongoing emissions resulting from continued practice change, all need to be considered for activities aimed at providing a permanent sink for carbon sequestration.  Further research is required to understand the bounds of this issue and when various underpinning mechanisms (which may be managed) dominate, and at what stage and in which environments increase $N_2O$ emissions risk negating sequestration gains.

## Case Study: Soil Condition Analyses System (SCANS)

The Soil Condition Analyses System (SCANS) can be used to monitor soil organic carbon content. The SCANS framework has five general components, and starts with the capture of prior information to characterise soil spatial variability to inform the soil sampling design and finally the estimation and mapping of soil organic carbon. Currently, the SCANS uses a mobile multisensor platform, with electromagnetic induction, gamma radiometric and accurate positioning sensors, to gather information on soil variability.  Cost and precision of measurement and baselining has been identified as a constraint to soil carbon farming and SCANS provides estimates of soil carbon with more precision at similar or lower costs to traditional approaches and provides better spatial estimates.  With this technology companies such as CARBONLINK are rapidly scaling to baselining hundreds of thousands of hectares of land for soil carbon projects.  SCANS provides a good example of how investment in measurement and verification technology can overcome barriers to uptake.  The instrument also provides key measures related to soil carbon fractions which can show the vulnerability of soil carbon stocks to loss which can help build confidence in the longevity of sequestration and can provide key measures of soil productivity assisting in aligning carbon projects with farmer co-benefits.




## 9.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt/yr) | Key evidence |
|---|---|---|
| **Technical Potential** | 115 | From Roxburgh *et al.* 2019– overcoming yield limits and converting annual to perennial pasture plus conversion of remaining cropping area to no-till, all summed (other options intersectional with these) |
| **Economic potential by 2025** | 0-3 | Companies expect to baseline and deliver 250,000 ha of projects this year growing to 500,000 in |

| | | |
|---|---|---|
| | | subsequent years (CarbonLink *pers. comm* August 2022), assuming projects yield 1 t $CO_2e$ $yr^{-1}$ results in close to 2M ha of activity |
| **Economic potential by 2035** | 5-29 | Current research and pricing should see this scale by 2035 to economic potential |
| **Economic potential by 2050** | 5-29 | Same categories as potential assuming calculations in this report |

**Table 9-2: Best estimate of soil carbon sequestration potential**

Estimates of total soil carbon loss from agricultural production systems is high: (Sanderman et al. 2017) estimated a global carbon debt (i.e., between saturated soil carbon and current levels) of 133 Pg C with the top 2 m because of agriculture. (Luo et al., 2010) estimate that approximately half the soil organic carbon in the topsoil has been lost under the Australian agricultural production system. (Karunaratne et al. , 2022) provide a spatial estimate of where soil carbon has been lost from Australian agricultural landscapes, see Figure 9-2. Summing pixels from this work suggests that under current management the Australian agricultural soil carbon deficit is around 5.4 GT C to a depth of 30cm. Without restoration of native vegetation over this area return of soil carbon to the pre-clearing stock level will not occur and to calculate the potential and economic sequestration potential we make calculations assuming the land is retained under agricultural practice.

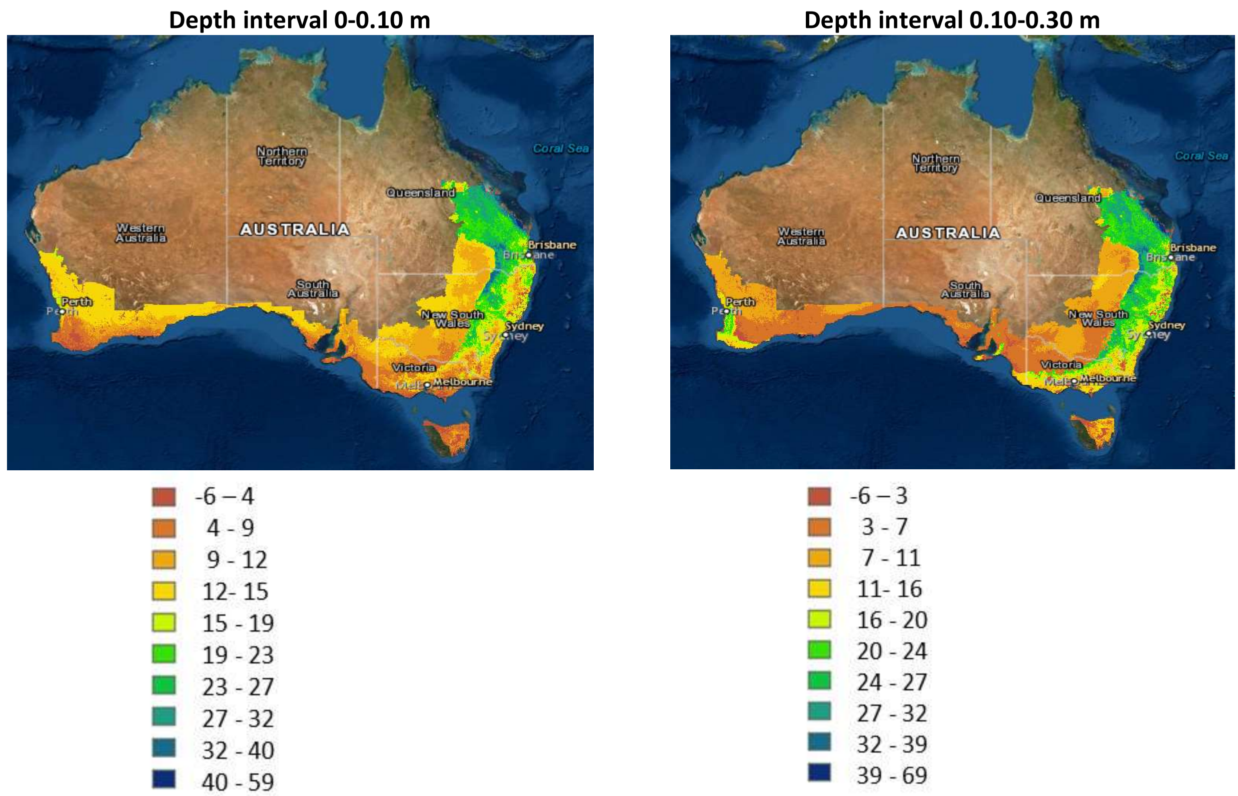



**Figure 9-2: Distribution of the soil organic carbon deficit stocks across major agricultural production regions of Australia. The spatial estimates were made for specified two depth intervals namely 0-0.10 m and 0.10-0.30 m, respectively. Values are express in C T/ha. (From Karunarante et al. 2022)**

There is evidence that management changes can increase soil organic carbon stocks (e.g. Sanderman et al. 2010; Hutchinson et al. 2007; Ogle et al. 2005) with rates of sequestration generally ranging between 0.18 and 2.9 t $CO_2$-e $ha^{-1}$ $yr^{-1}$.

Estimates of how soil sequestration translates to national sequestration potential are highly variable. Taken across Australia's cropping and grazing lands, early meta-analyses suggested a range from below 1 to above 55 Mt $CO_2$-e $ha^{-1}$ $yr^{-1}$ (https://theconversation.com/how-much-carbon-can-trees-absorb-5829) , and even higher estimates of up to 103 million ACCUs per year from industry estimates (Commonwealth of Australia 2021) have been recently made (Australian Carbon Credit Unit's (ACCUs) are a financial instrument awarded to eligible energy efficiency, renewable energy generation and carbon sequestration projects that result in a reduction of Greenhouse Gas (GHG) emissions. One ACCU represents the avoidance or removal of one tonne of carbon dioxide equivalent (tCO2-e) GHG).

The most rigorous analysis of potential under the existing 'measurement of soil carbon sequestration in agriculture systems (2018)' methodology is an unpublished CSIRO analysis (Roxburgh et al 2019.). It is worth noting that new methods have been developed since this analysis and further investment into new modelling and measurement approaches will change project costs which may further unlock opportunities. Roxburgh et al 2019 only considered the *Estimating Sequestration of Carbon in Soil Using the Default Values* (2015) methodology and approaches applicable in *Measurement of soil carbon sequestration in agricultural systems* (2018). The later method has been closed and is replaced with *Estimating soil organic carbon sequestration using measurement and models method* which recognised two additional practices of 1) use legume species in cropping or pasture system, and 2) use a cover crop to promote soil vegetation cover or improve soil health or both. The addition of these changes may increase the rate of adoption, however they are unlikely to materially change the estimated quanta of sequestration (which is fundamentally land limited).

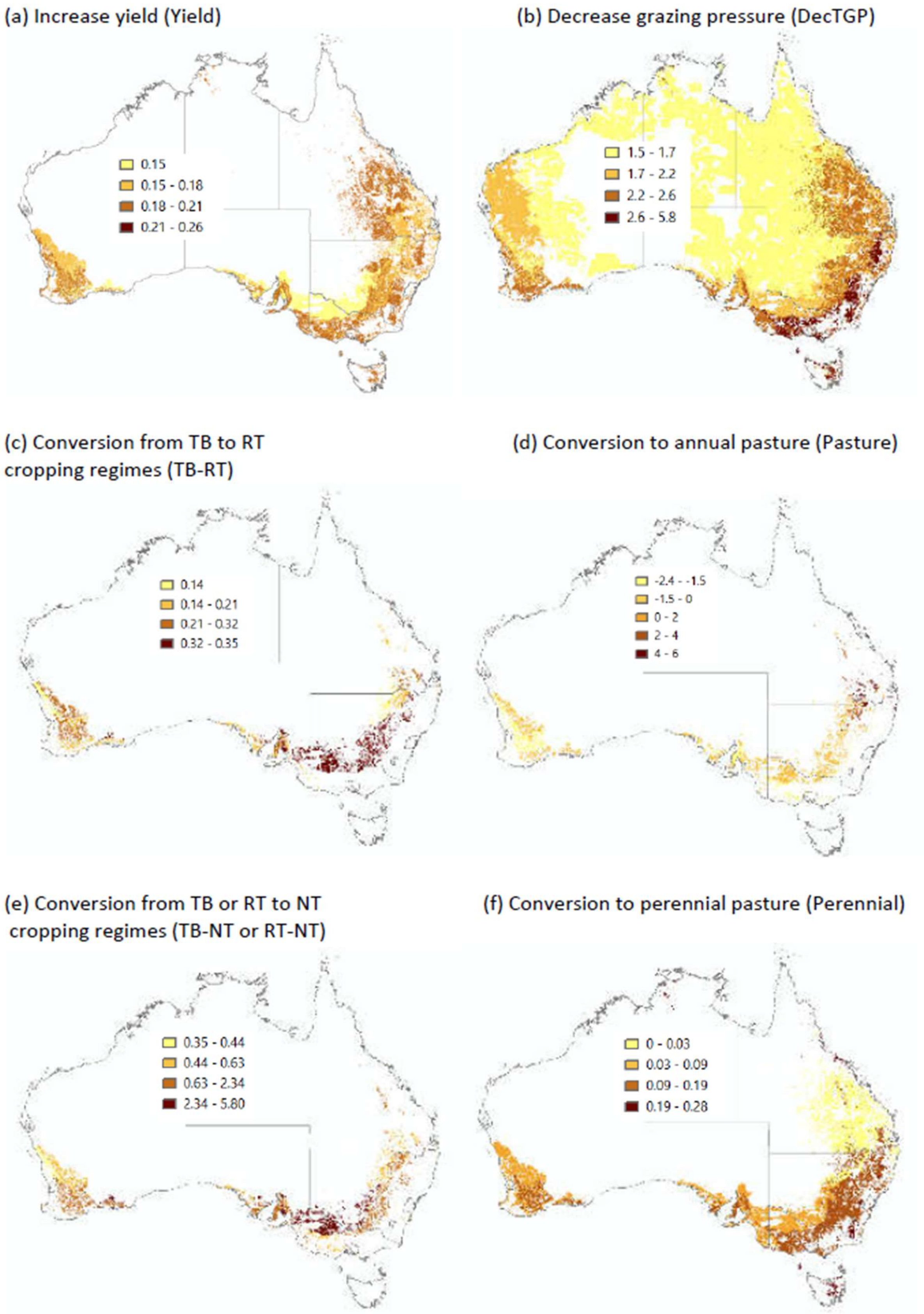



**Figure 9-3: Average annual (25-year) sequestration (t CO2-e yr-1) for each of the six classes of management intervention to build soil carbon. Labels are those in Table 9-3.**

This study (Roxburgh et al. 2019) applied FULLCAM to predicted changes in measure 0-30cm SOC during a 30-year period across 75 spatial zones. The work assessed four land use: Grazed Native Vegetation, Dryland Crops, Modified Pastures and Dryland Horticulture. Crop land was further sub-divided based on the proportion of this land that is currently managed as either: (i) tilled crops where stubble is burnt and ploughed; (ii) non-tilled crops where stubble is incorporated into the soil via ploughing ; and (iii) non-tilled crops where stubble is left standing. These proportions were based on those applied by DoEE (2019b), which in turn were based on data collected by ABS (2019). Land use changes therefore were applied as per Table 9-3 below:

| Land use | Yield | DecTGP | Perennial | Crop-Pasture | TB-NT or RT-NT | TB-RT |
|---|---|---|---|---|---|---|
| **GNV** | | X | | | | |
| **Modified Pasture** | X | X | X | | | |
| **Crop_TB** | X | | | X | X | X |
| **Crop_RT** | X | | | X | X | |
| **Crop_NT** | X | | | X | | |

**Table 9-3: Six different management change options (increase yield, Yield; decreased total grazing pressure, DecTGP; conversion of annual to perennial pasture, Perennial; conversion of crops to pasture, Crop-pasture; conversion to no -till, TB-NT or RT-NT; conversion to reduced till, TB-RT) were simulated, with many alternatives being available for land used for Grazed Native Vegetation (GNV), modified pasture, crops that are tilled and burnt (Crop_TB), crops that are reduced tilled (Crop_RT) and crops that are non-tilled (Crop_NT).**

Soils were initiated with soil carbon pool values drawn from Viscarra Rossel et al. (2015). A generic set of FullCam parameters were derived and are available on request.

The modelling results of soil carbon change per hectare are shown in Figure 9-3.

### 9.3.1 Technical sequestration

| Approach to increasing soil carbon | Maximum technical sequestration (25 year annual average) (Mt $CO_2$ e yr $^{1}$) |
|---|---|
| **Increase crop or pasture yield** | 50.7 |
| **Decrease grazing pressure** | 12.3 |
| **Convert annual pasture to perennial pasture** | 61.6 |
| **Convert cropland to annual pasture** | 54.0 |
| **Convert to no-till** | 3.04 |
| **Convert to reduced till** | 1.18 |

**Table 9-4: Technical sequestration from application of different approaches to increasing soil carbon. Note quantities cannot be added as there is area overlap**

### 9.3.2 Economic sequestration

Economic potential estimates were made using the FullCAM model for each sub-activity. Assumptions made in modelling are given in Roxburgh et al. 2019. High end and low-end estimates assume existing constraints and requirements under the ERF methods and assume a carbon price of $10 and $30 per tonne respectively. A hurdle rate for land use and practice change of 1.2 was used (that is adoption was of the new practice was not assumed to happen till the new land use and carbon price return exceed prior land use value by 20%). It is worth noting that these estimates of economic potential reflect one set of institutional arrangements around sequestration (ERF) and that other market framings may be less onerous (say for example Regen Network's method ( https://www.regen.network/) which was used in the recent Wilmot Cattle Co soil carbon trade (Wilmott trade The Conversation ). These relaxation in terms of spatial realisation is essentially the same in the modelling of increasing the carbon price and for these less onerous market mechanism the higher carbon prices may better reflect the economic potential carbon sequestration.

It is worth noting that the economic sequestration potential in this analysis is broadly based on the costs methodologies reviewed by Roxburgh et al. (2019) and does not allow for the 2021 methodology nor future advances in model-measured approaches that can reduce sampling intensity and frequency.

| Approach to increasing soil carbon | 25yr average annual sequestration (Mt $CO_2$ e $yr^{1}$) | Area (MHa) |
|---|---|---|
| Increase crop or pasture yield | 0.61 – 1.08 | 1.0 – 1.6 |
| Decrease grazing pressure | 0.07-0.64 | 0.5-8.9 |
| Convert annual pasture to perennial pasture | 4.8-27.5 | 0.7-7.2 |
| Convert cropland to annual pasture | 0.33-0.93 | 0.15-0.32 |
| Convert to no-till | 0.0-0.25 | 0.0-0.6 |
| Convert to reduced till | 0.0-0.25 | 0.0-0.6 |
| **Total** | 5.81-30.65 | 1.72-19.22 |

Table 9-5:Economic sequestration associated with the Soil Carbon activities. The ranges reflect two carbon **price assumptions, $15 t CO2-e (lower bound) and $30 t CO2-e (upper bound).**

It is important to note that adoption of conservation practices (reduced/no-till, stubble retention) is significantly higher in Australia (74% in 2016) compared to that globally (12.5%, 2016; Pratley & Kirkegaard 2019), perhaps limiting the capacity of tillage practice change to have ongoing sequestration benefit. The ability to estimate change potential associated with emerging practices in Australia is less well supported by temporal soil carbon data. Emerging practices include those that promote regenerative approaches, strategic deep tillage that overcomes subsoil constraints, and clay delving or spreading practices.

## 9.4 Technology Readiness Potential and Commercial Readiness

### 9.4.1 Technology Readiness

| $ per tonne $CO_2$e | $ per tonne $CO_2$e | Key Evidence |
|---|---|---|
| **TRL9** | $7-13 for low and high yielding projects. This does not include the transaction costs beyond activity change and measurement costs. | Bhattarai and McCosker (2019) undertake calculations assuming an activity change of $50.h-$^{1}$, an average sequestration rate of $2t.ha$^{-1}$.yr$^{-1}$ detectable at 95% confidence every 5 years and a baseline and measurement cost of $44.ha-$^{1}$ for a 1000 ha project with 6 strata and 5 plots per strata. Recent figures suggest technology improvement and scale change this and best estimate (Andrew Gatenby, CarbonLink August 2022) suggests for a 5000ha project set up and baseline is $30.ha-$^{1}$ and then 5x 24 assessments. Sequestration rates anticipated appear high as studies suggest that the average change in soil C in the top 30cm after 50 years across Victoria ranges from 21 t.ha$^{-1}$ (77 t $CO_2$-e.ha-$^{1}$) to 6.5 t ha-$^{1}$ (23.8 t $CO_2$-e |

| | |
|---|---|
| | ha-[1]) under a zero till grain rotation (Robertson and Nash 2013). For calculations we assume 0.5 t C $ha^{-1}$ .$yr^{-1}$ or 1.8 t $CO_2$- $ha^{-1}$.$yr^{-1}$. Assume project runs 25 years =45 t C $ha^{-1}$, costs are $50, baseline. For the lower yielding projects in the Victorian case study assume 0.5 t $CO_2$-e $ha^{-1}$.$yr^{-1}$ giving 12.5 t C over 25 years. No allowance for any risk reversal buffer or conservative assessment of accrued carbon. |

**Table 9-6: Technology readiness assessment for soil carbon technology**

### 9.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| **3-4** | Projects being established in niche areas, some emerging competition between project providers. Despite cost analysis above suggestion that upfront project development cost constraining activity scaling. Increasing number of projects year or year suggests commercial viability |

**Table 9-7: Commercial readiness assessment for soil carbon technologies**

## 9.5 Scalability, Length of storage, Measurement and Verification

### 9.5.1 Scalability.

There are three broad ways to incentivise the building of soil carbon:

- direct subsidy to limit practices that run-down soil carbon;
- payment to sequester soil carbon;
- and, market or value chain mechanisms that reward practices that build soil carbon.

Depending on the instrument used to incentivise soil carbon sequestration, different assessment accuracy may be required, differing levels of uncertainty tolerated, and the costs of measurement and monitoring that can be supported by protagonists will vary.

All approaches, however, require some level of reliable and cost-effective quantification of change and benefit. The extent to which the cost of this monitoring and verification creates a barrier to application of practices depends on the financial returns for applying practices (a function price or payment, and if payment per unit of sequestration the change in soil carbon and the proportion of the change that is credited) and the value place by the funder of practice change of additional co-benefits that result from the new practice. These co-benefits might include increased productivity or improved farming system resilience to events such as drought, the avoidance of costs into farming due to improved soil condition and health, and any additional market value realised through demonstration of best-practice farming or management, or public value attached to improved landscape values.

There have been high levels of recent interest in soil carbon methods (and high levels of contracting in relation to many ERF methods) though to date delivery few ACCUs have been issued (see table 6.1). There is rapidly growing interest in methods and a fast growth in areas contracted. CarbonLink for example (pers. comm. Andrew Gatenby, CarbonLink August 2022) expect to baseline 250,000ha in the next 12 months and see this potentially double in subsequent years. Feedback from carbon industry participants (Soil Carbon Industry Group *pers comm* 2020) suggested the following factors, in order of importance, affected the uptake of soil carbon projects: the rate of sequestration in many projects is slow so returns per year are slight; the conservative nature of the direct measurement method in the ERF which recognises the 60% exceedance value from the cumulative distribution curve reduces returns to projects; project scale is important because there is a significant proportion of fixed costs relative to variable costs; and finally measurement cost to meet MRV requirements. Current modifications to methods (the 2021 ERF method) that looks to take a modelled-measured approach may overcome some of these constraints.

### 9.5.2 Length of storage

It is important to remember that when we measure a change in Soil organic carbon (SOC) we are measuring a net stock change, and not the permanence of any soil carbon molecule. Practice changes that lead to increased soil carbon are changes in the equilibrium between inputs and outputs, there is strong evidence to suggest that if the practices that built soil carbon are ceased and revert to a prior practice that soil carbon stocks will revert to the pre-intervention level, or the old equilibrium value.

SOC is composed of fractions or pools of different kind. These different fractions of soil carbon have different length of storage in the soil. Three SOC fractions are commonly recognised: particulate organic carbon (POC; residency time ~7 years) which is at risk from loss; humic material (HOC; residency time ~50 years), which is relatively more stabilised; and resistant organic carbon (ROC; residency time >100 years), which is resistant to decomposition, and includes charcoal and charcoal-related compounds. Practices that increase POC but make little change to HOC or ROC create soil carbon stocks that might be particularly vulnerable. The ration of POC to (HOC+ROC) has been used as a vulnerability measure for SOC (Viscarra Rossel 2019).

In addition, some soil attributes increase the risk of soil carbon reversal. For example, soils that offer little physical protection to decomposition (sandy or low clay soils). Soils that are considered carbon saturated have little capacity to physically protect any more carbon from decomposition, and organic residues entering the system will naturally be decomposed to $CO_2$.

Things that change the nature of the equilibrium between inputs and outputs can affect the length of storage. Carbon stocks go up and down with seasonal variability, especially rainfall which strongly drives photosynthesis and inputs. If there is directional change in these driving variables with climate change, we might see less inputs resulting in a lower equilibrium value and hence lower time averaged stocks.

### 9.5.3 Measurement and Verification

Measurement of soil carbon (and hence verification) is not straight forward and this presents challenges for markets. The following section discussions three approaches to measurement: direct measurement, proximal and remote sensing and modelling. These are not mutually exclusive, and it is likely that some level of direct measurement (though not necessarily at the project level) will be required to support estimates of bio-sequestration (even if only to provide starting points for models ).

Paustian et al. 2019 and Sanderman et al. 2010 summarise the general difficulties of soil sampling.

1. **Current approaches require an estimate of bulk density.**

   Calculation of soil organic carbon requires both the concentration of carbon in a sample and the bulk density and the later requires volumetric soil samples that are laborious to collect and analyse. Bulk density is required to ensure that concentration is measured at each measurement on an equivalent soil mass. The reason for this is that a more compacted soil will contain more mass to a given depth and thus appear to contain more carbon, and without correction, practices that compact the soil may give the impression of increasing carbon stocks whereas they may simply be increasing volumetric concentration due to compaction. Bulk density is extremely difficult and time consuming to measure due the heterogenous nature of soil texture, structure, compaction and gravel content.

2. **Current measurement is laborious, using manual processing to prepare soil for analysis and remove coarse fractions and roots.**

   Soil samples must be dried, crushed, sieved and ground to ensure representative samples are analysed: essentially the sample is homogenised. The process is laborious and time consuming.

3. **Soil organic carbon is highly variable in space**

   In all ecosystems, but particularly for those with patchy vegetation, such as most of Australia's rangelands, there can be large spatial gradients in SOC stocks. For example, Jackson and Caldwell (1993) and Robertson et al. (1997) found a 5-fold variation in SOC content within sagebrush-steppe vegetation and agricultural fields respectively. At the meso-scale soil carbon varies with topography, and at the macro-scale with soil type, climate and landscape history. Bhattarai and McCosker (2019) show that the consequence of this variability is that a high number of samples are required per carbon estimation area to detect modest levels of soil carbon change with high confidence: in their study approximately 200 samples where required in an example carbon estimation area to detect a 10% change in soil organic carbon with 95% confidence in CEAs between 500 and 8000ha.

4. **Soil carbon response to management practice is variable in time and with depth**

   Soil organic carbon varies with soil depth and detecting overall changes requires accounting for the vertical gradient in soil organic carbon. In addition to varying with soil type and texture, the gradient in soil carbon is influenced by tillage and management (Paustian et al 2019). Within season, soil carbon stocks will vary with variation in carbon inputs. In a wheat-fallow system, Wang *et al*. (2004) found that total soil carbon stocks in the top 10 cm decreased by 10% between early to mid-fallow (December and March sampling dates) and late fallow (July).

   Year-to-year variability in temperature and especially soil moisture and their effects on decomposition rates and net primary production influence soil carbon stocks and inputs and over inter-annual time frames may overwhelm any anticipated soil organic carbon response to a change in management (Sanderman et al. 2010). In general decomposition will be higher in warmer and wetter conditions. Soil moisture is a key driver of plant growth, and hence inputs into soil carbon over much of Australia where net primary production is rainfall limited.

   Conversion of land from native vegetation to agriculture has typically reduced soil organic carbon stocks in the order of 20-60% from pre-clearing levels (Sanderman et al. 2010, Luo et al. 2010). Sanderman and Baldock (2010) discuss that without time series data relative gain in soil carbon may be due to a reduction or cessation of soil carbon losses rather than an actual increase in stocks. Whilst recognising that such a change would result in net gains relative to business as usual land management, such changes would not offset emissions elsewhere as drawdown would not occur.

   There has been, and continues to be, considerable redistribution of topsoil across Australia that is both difficult to measure and influences soil measurement and modelling. The implication of omitted soil redistribution dynamics in SOC accounting is to increase uncertainty and diminish its accuracy (Chappell et al. 2012).

5. **The signal to noise ratio is low**

Changes due to management practices are small relative to the background level of carbon stocks. Paustian et al. 2019 suggest that the change we are trying to detect in a typical soil is around 1% per annum or less of the existing stocks, and hence measurement intervals of 5 years or more are required to detect statistically significant changes.

#### 9.5.3.1 traditional wet chemistry approaches

With current technology, accurate direct measurement of SOC requires 'destructive sampling', i.e., soils taken from the field and then sent to a laboratory for processing and analysis. There are two main reasons for this. First, conventional analysis methods to determine C content as a % of total soil mass, i.e., both dry and wet oxidation methods, require laboratory-scale instruments and facilities that are not practical to bring to the field. The concentration of organic C in a soil sample is usually determined by converting a sample to $CO_2$ by either wet oxidation (i.e., Walkley and Black 1934) or dry combustion (i.e. Wang and Anderson 1998) and then quantifying the amount of $CO_2$ evolved. Correction factors are required if the wet oxidation method is used as it is known to underestimate organic carbon. Soils must be carefully processed and standardised – i.e., sieved, homogenised, dried and finely-ground, for the analyses. Secondly, accurate measurement of soil bulk density (i.e., mass per unit soil volume) requires a known volume of soil to be weighed under standard oven-dry moisture conditions, necessitating soil collection from the field. The collection, transportation, and processing of soil adds considerable time and costs to the operation.

#### 9.5.3.2 Proximal sensing approaches to soil measurement

Proximal soil sensing refers to the development and use of sensors in the field or lab, which obtain signals from soil when the sensor's detector is in contact with or close to (within 2 m) of the soil (Viscarra Rossel et al. 2011). The topic has recently been reviewed (England and Viscarra Rossel 2018). With respect to soil carbon estimation, proximal sensors can be used to predict: (a) soil carbon concentration, (b) bulk density and the (c) gravel content in the soils (England and Viscarra Rossel 2018).

a. **Soil carbon concentration.** Both in-situ, and ex-situ spectroscopic proximal sensing techniques are used regularly to determine carbon concentration and its forms. The visible and near infrared (VIS-NIR) regions of the electromagnetic spectrum are the most widely used (Viscarra Rossel et al., 2006). The specific absorptions in this region are important to determine soil carbon concentration through empirical modelling approaches commonly known as chemometrics. However, prediction of different soil carbon fractions with different turnover times are more accurate when it is scanned and modelled using datasets gathered using mid-infrared (MIR) region of the electromagnetic spectrum (Baldock et al., 2013). Both NIR and MIR spectroscopic techniques can be used in field conditions but require adjustment for moisture contents (Minasny et al., 2011). Recent advances have been made with chemometric modelling approaches through use of modern data mining and modern machine learning techniques such as convolutional neural networks (Viscarra Rossel et al., 2018; Ng et al., 2020). To predict soil organic carbon an empirical model needs to be developed to relate the spectra to physically measured soil data (such as dry combustion analysis of the same sample).

   Key areas of research to improve utility of the approach are: (a) ability to standardise spectral datasets acquired from sensors manufactured by different vendors; (b) recognising that new sensors on the market have differing spectral ranges and resolutions and therefore require standardisation to fit existing protocols; (c) development of spectral information systems that enable near real time predictions with automated updates of underlying chemometrics models when new datasets are available; (d) improvement in model predictions through the inclusion of covariates reflecting soil management history and local factors. Since soil carbon affects the soil colour, it is possible to use soil colour to get an estimate of soil carbon content in the soil though colour. However, the model accuracies are dependent on the carbon concentration present in the soil and colour calibrations are very specific to soil types, although attempts have been made to develop user friendly inexpensive mobile apps to predict soil carbon contents (Aitkenhead et al., 2016). Currently, and possibly not at all, this approach has low discriminatory power and may not be useful for general soil assessment.

b. **Bulk Density.** Active gamma-ray attenuation (AGA) can be used to estimate soil density via the attenuation of the radiation by the soil, as defined by Beer–Lambert's Law. Lobsey and Viscarra Rossel (2016) provide a detailed description of the use of AGA for measurement of soil bulk density. In summary, the measurements are made axially through a soil core and the attenuation of gamma radiation passing through it to the scintillation detector is proportional to the density of the soil. This method requires sampling of intact soil cores and measurement under field conditions, so correction for water content is required. This method has advantages over the traditional lab-based method of determination of bulk density as no other sample preparation is required.

c. **Gravel content.** The most promising approach for proximal sensing of gravel (and bulk density) of soil is the use of X-ray computed tomography (CT) with strong positive correlations (>0.8) obtained in studies (Fouinat et al 2017). Deployment into field instruments requires the ability to rotate the soil core around the sensor.

#### 9.5.3.3 Remote sensing technology and soil carbon measurement

Remotely sensed datasets are used for earth observations as a cheap and rapid assessment tool. For soil carbon, a key question is how remote sensed variables can be used as surrogates for variables in soil carbon models. Remotely sensed datasets can be included as model drivers in the (a) stratification of carbon estimation areas for efficient and low variance sampling; b) empirical soil carbon models (Viscarra Rossel et al., 2014) and (c) process-based models (Karunaratne et al., 2015).

Traditionally, upscaling of point observations of soil carbon across the landscape, together with other attributes such as terrain, soil type, and optical remote sensing datasets, including raw reflectance bands along with a variety of soil/vegetation indices, are used as model drivers. The outputs of such analysis provide a static digital soil carbon map across the landscape (Viscarra Rossel et al., 2014). There is, however, an opportunity to explore newly deployed and up and coming satellite sensors for development of soil carbon estimation with next generation soil carbon models. Key changes have been the recurrence of imagery, and the improved spectral and spatial resolution which allows a more refined set of variables to be monitored. Over the years the spatial, temporal, spectral and radiometric resolution of satellite datasets have improved significantly allowing capture of land management practices and condition more precisely, even within the growing season e.g. Sentinel program managed by the European Space Agency. As a result, drivers of soil carbon are measured directly or via proxies. For example, fractional cover datasets provide proportional allocation of photosynthetic, non- photosynthetic and bare soil fractions for a given pixel with a satellite image (Guerschman and Hill, 2018). These satellite products can be used as proxies for land management including land cover which is an important driver for spatial and temporal modelling of soil carbon. Additionally, time series of vegetation indices such as greenness or LAI from NDVI spectra can represent the crop and pasture biophysical characteristics and be fused (that is combined with static parameters) with model drivers of development in next generation soil carbon models. Recently, a satellite derived biophysical model, called Crop-C was developed by CSIRO which enable the prediction of crop yield of Australia's major grain crops, and of course yield is related to the below ground inputs and hence soil carbon addition rates all other things being equal and accounted for (Donohue et al., 2018). This opens a new avenue for incorporation of satellite derived inputs into biophysical models that can be downscaled to paddock or sub-paddock scale.

A further emerging field is the fusion of multiple remote sensed data streams of differing attributes and/or spatio-temporal resolution (e.g Weiss et al. 2020; Lin et al. 2020).  This advantage occurs because remote sensing images with high spatial resolution are mainly limited to a few spectral bands, and a limited number of intervals per year (such as Landsat) whereas images with high spectral and temporal accuracy are often provided at low spatial resolutions (such as Modis).

With recent advances in cloud computing and data science, remote sensed data streams are being rapidly converted to high spatial and temporal resolution satellite derived products representing land management practices and parameters. These products will play a key role in development and updating of next generation process-based soil carbon model. For example, advances have already been achieved in: (a) extraction of field/paddock boundaries (Waldner and Diakogiannis, 2020); (b) agricultural management practices (Zhao et al., 2020) and (c) estimation of crop yield and pasture biomass using space-borne sensors (Chen et al., 2020) which can be incorporated as biophysical model inputs, reducing overall uncertainties associated with modelling. Such data driven approaches will enable replacement of the traditional lookup tables (updated in five-year intervals, and at large spatial footprint average) generated through Agricultural Census Statistics that are generally used within the soil carbon models. Incorporation of remotely sensed datasets will be able to update such model inputs more frequently capturing both inter-, intra- seasonal variability for more realistic modelling of soil carbon. This is not to downplay the significant challenges that lie ahead in fusing these remotely sensed variables with parameters in process-based models: a key consideration is that although remote sensing products are related to model or biophysical parameters, and correspond some of the time, this is not always the case (Weiss et al 2012) and will represent challenges for models largely derived from terrestrial based measurement.

At farm scale, there is a growing interest among agronomists and landowners in the use Unmanned Aerial Vehicle (UAV - drones) mainly as a monitoring tool for agronomic practices. There is an untapped potential to utilise datasets gathered through UAV, to derive very high spatial resolution digital soil carbon maps at farm scales. These UAV-borne systems are less impacted by cloud cover and additional radiometric calibration steps generally required by passive remote sensing satellite systems such as Sentinel 2/Landsat 8. The datasets generated using a standard RGB or multispectral sensor mounted on a UAV enables generation of spectral and 3D datasets that represent the characteristics of crop/soil (in space and time) that are important model drivers of soil carbon across the landscape. There is also a growing interest in utilising 3D datasets generated via state-of-the-art passive algorithms such as Structure from Motion (S*f*M) (Wijesingha et al., 2019). Such datasets provide information on crop/pasture height (a proxy for crop growth/biomass) and can be used to generate very high spatial resolution primary and secondary terrain attributes that later can be fused to develop soil carbon models.

#### 9.5.3.4 Soil carbon modelling, model data fusion approaches and machine learning approaches

Soil carbon models are used to simulate carbon over time with different model inputs and using model parameters. There are more than 250 models used to simulate soil carbon (Manzoni and Porporato, 2009). These models work in a wide array of spatial scales from a few mm to km scales across landscapes. Classification of these models is difficult since these models are based on a wide range of physical, biogeochemical processes and also the underlying assumptions vary significantly among the models. Batlle-Aguilar et al. (2011) and Manzoni and Porporato (2009) classified these models based on their internal structure: (a) process oriented (multi) compartment models; (b) organism oriented (food web) models; (c) cohort models describing decomposition as a continuum; (d) a combination of model type (a) and (b). Of these model types, the process oriented models (compartment models) vary from simple to more complex models (e.g. RothC model, Century model, FullCAM) with differences in the number of compartments representing varying states and forms of organic C, with different turnover rates (biological degradation) (Smith et al, 1998). The differing levels of representation impact on the detail in measurement required for initialisation but also influences the ability of the models to assess feedback and interactions in climate and practice and to allow an analysis of risk to sequestered carbon change from changing conditions and practice (that is the proportion of sequestered carbon that is in pools that may rapidly turnover).

Recent advances in soil carbon modelling comprise: (a) use of digital datasets as model inputs; (b) improvements in model initialisation; (c) advances in model calibration and model uncertainty assessment and (d) use of model fusion techniques. In terms of model inputs, there is an opportunity to improve the simple water balance sub-model used in some soil carbon model (e.g. RothC/FullCAM model) and instead use the digital water balance model derived from Soil Landscape Grid of Australia (SLGA), SILO climate datasets and remotely sensed ET datasets (Wimalathunge and Bishop, 2019). This will provide more realistic soil moisture values that drives decomposition of incoming organic matter to soil compatible with the Australian landscape conditions. Some improvements have already made using digital layers using the spatial datasets from SLGA of Australia to provide more realistic soil inputs for such model (e.g. clay contents digital soil map within FullCAM model). Additionally, the satellite derived products representing land management decisions, as explained above, can be used as model inputs for soil carbon models.

Another key compartment of the model uncertainty is associated with the model initialisation in the landscape context. The replacement of conceptual soil carbon pools with measurable soil carbon fractions enables initialisation of such models in landscape without prior history of the land use (Baldock et al., 2013). The alternative is to spin up models with a long, simulated land use history to initialise starting pools with inherent uncertainty. Luo et al. (2017) used 90 field trials at 28 sites across the different agroecosystems in the Australian cropping regions and found that C inputs accounted 27% of the relative influence on soil carbon rate change, followed by climate 25% (i.e. precipitation and temperature), soil C initialisation pools 24% and other soil properties (e.g. clay content) 24%. This highlighted the importance of model inputs to maintain model simulation quality and reduce the main sources of uncertainty in soil carbon models. Uncertainty arises in many ways in modelling soil carbon, through model inputs, parameters, representation of dynamics and model predictions. The total uncertainty is often poorly represented, and prior knowledge about the uncertainty of model parameters (say our knowledge of practice application uncertainty) is not easily translated into model estimates. Advances in Bayesian hierarchical modelling are improving the uncertainty estimation, and this can be translated into improved confidence intervals for soil carbon change (Clifford et al., 2014).

Datasets are required for soil carbon model calibration and validation. Especially useful for calibration and validation are data sets from long-term trials with weather, management and vegetation, crop and productivity history. The best current national datasets were compiled by Skjemstad and Spouncer (2003). Updating this database to reflect modern crop and soil management practices is needed. Additionally, between 2009-2012, CSIRO coordinated a national scale soil carbon research program (SCaRP) which provided a detailed understanding of soil carbon and its fraction status across the main cropping and pasture growing regions in Australia. These samples, however, only provided a point in time snapshot. With the passage of nearly ten years since first measurement, resampling of selected sites will provide much-needed knowledge on change of soil carbon across the continent-scale. Additionally, some of these sites can be converted as long-term soil monitoring network of Australia coordinated by the national science agency with the participation of all states and territories. Current work funded by the Federal Government is under way to resample approximately 7% of the original SCaRP sites. The spatial-temporal datasets gathered through such soil monitoring network will be foundational for the next generation soil carbon models that will be required to underpin a model-measured methodology.

The application of machine learning (ML) modelling of soil carbon has increased rapidly in the last decade (Padarian et al 2020), though sparsity of data has limited space-time modelling ( Padarian et al. 2020). While ML models for soil carbon prediction can have better predictive performance than traditional methods (Padarian et al 2019), interpretability can be low and reduce confidence in their use for decision making. For managers and policy makers this presents a tricky set of decisions: do we aspire for the greatest prediction even if it comes at the cost of transparency? While confidence in both ML and process-based models (such as RothC model) should be constrained to the domain of the inference data set, modelling that explicitly captures our understanding of system functioning and the feedbacks in process may provide more confidence in extrapolation and into novel combinations of systems. There is a clear opportunity to link mechanistic/process-based modelling with statistical/ML approaches to improve predictions, particularly to better characterise in models.

## 9.6 Social, environmental impacts, risks and co-benefits

### 9.6.1 Social impacts and risks

Soil carbon farming can provide a requirement that future managers of that land to maintain practices to retain carbon stocks. This will reduce future management flexibility, say should the farm wish to target different product markets, and can be a disincentive because permanence is required for soil sequestration options to be effective. Where a strong alignment between increasing soil carbon and improving or restoring farm productivity or resilience exists, this is not the same issue and potentially offers a win:win provided risks can be managed.

### 9.6.2 Environmental impacts and risks

Sustaining soil carbon requires net primary production to be maintained. In some parts of Australia there is a drying trend associated with climate change and projections, and in Australia net primary productivity is strongly correlated with rainfall posing a threat to soil carbon. Declining rainfall is already impacting potential crop productivity and will continue to do so into the future (Hochman et al 2017), though to date technology improvement has prevented loss of production despite a 20-30% decrease in the theoretical water-limited yield (Hochman et al. 2017; Fletcher et al. 2020). This may be exacerbated by drives to increase the harvest index of crops, increasing allocation of carbon to grains and thus reducing the amount that remains as stubble or root inputs to soil. Roxburgh et al. (2020) carried out a meta-analysis of climate change effects on soil carbon found a range of negative and positive interactions with climate factors but concluded that there was a moderate to high risk to soil carbon stocks from climate change.

Sequestering carbon also locks up macro nutrients such as nitrogen, sulphur, and phosphorus due to the stoichiometry of soil organic matter, which affects long-term costs of increasing soil carbon (Kirby et al. 2013). However, it is important to note that past productivity may in part be due to the release of these nutrients from soil organic matter that has been lost over time – commonly referred to as nutrient mining.

Finally, because practices that increase soil carbon need to be maintained over the long run to maintain soil carbon increases, it is important to look at net emissions over integration periods relevant to atmospheric outcomes. Luo et al. (2017) showed that for fertiliser addition to crops, while systems acted as sink for the first few years, over the longer term some systems can become net emissions sources. The balance of carbon-to-nutrients (stoichiometry) is an important driver of both soil carbon sequestration and risk of N2O emissions. The changes in the rate of soil carbon accumulation over time and the ongoing emissions resulting from continued practice change, all need to be considered for activities aimed at providing a permanent sink for carbon sequestration. Further research is required to understand the bounds of this issue and when various underpinning mechanisms (which may be managed) dominate, and at what stage and in which environments increase $N_2O$ emissions risk negating sequestration gains.

### 9.6.3 Co-benefits

There are many good reasons to reduce soil carbon loss and improve soil carbon stocks. Increasing soil carbon is associated with a range of productivity and environmental benefits, including improvements to soil structure, soil fertility, nutrient retention, water holding capacity, and reduced soil erosion (Janzen

2006; Sanderman et al. 2010). Many studies have shown a strong correlation between increased SOM levels and improvements in soil physical properties such as aggregation, water infiltration, hydraulic conductivity and compaction (e.g. Blair et al. 2006a; Blair et al. 2006b; Whitbread et al. 2000).

Co-benefits of soil organic carbon include therefore include:

- sustaining and improving productivity.
- reducing the need for fertiliser inputs; (Yeboah et al 2021)
- reducing drought impacts (Bowling et al 2020, Lobell et al 2020, Yeboah et al 2021);
- and reducing externalities such as dust storms (Sivakumar and Stefanski 2007).

## 9.7 Barriers to implementation:

### 9.7.1 Policy and regulatory environment

Soil carbon methods are well supported by existing regulation.  As discussed, earlier industry proponents have claimed that the monitoring, reporting and verification barriers are significant barriers to entry.

### 9.7.2 Social licence and stakeholder acceptance

Generally, soil carbon projects are positively received and the alignment to other co-benefits well documented.  Recent sale by RegenAg of soil carbon credits to Microsoft (noting that these were not credited through the ERF or under an ERF method) attracted commentary on the sale of Australian soil sequestration overseas ( The Conversation 25/6/2021).  As part of this commentary questions on assessment methodology were raised and concern that methodologies (in comparison with the ERF methods which place a high premium on monitoring and verification approaches) should not undermine the integrity of soil carbon trading.

### 9.7.3 Technology performance variability

Cost of soil sampling remains a barrier to entry.  Traditional we chemistry approaches to soil carbon measurement are challenging.  With current technology, accurate direct measurement of SOC requires ‘destructive sampling’, i.e., soils taken from the field and then sent to a laboratory for processing and analysis. There are two main reasons for this. First, conventional analysis methods to determine C content as a % of total soil mass, i.e., both dry and wet oxidation methods, require laboratory-scale instruments and facilities that are not practical to bring to the field. The concentration of organic C in a soil sample is usually determined by converting a sample to $CO_2$ by either wet oxidation (i.e. Walkley and Black 1934) or dry combustion (i.e. Wang and Anderson 1998) and then quantifying the amount of $CO_2$ evolved.  Correction factors are required if the wet oxidation method is used as it is known to underestimate organic carbon. Soils must be carefully processed and standardised – i.e., sieved, homogenised, dried and finely-ground, for the analyses. Secondly, accurate measurement of soil bulk density (i.e., mass per unit soil volume) requires a known volume of soil to be weighed under standard oven-dry moisture conditions, necessitating soil collection from the field. The collection, transportation, and processing of soil adds considerable time and costs to the operation.  Physical sampling and measurement will always be required for calibration and validation of other methods, be they proximal or remote sensed.  However, efficiencies can be made and some of the more laborious steps may be replaced with proximal sensing approaches. Emerging proximal sensing techniques, now recognised in methodologies provide another way forward.  Proximal sensing of soils is more cost-efficient though more costly than existing soil sampling approaches but produces more accurate estimates.  Even although with existing methods the costs over the life of a project are similar the costs are higher upfront and this can present a cash flow problem for participants.  Near to present technological modifications to existing proximal sensing technology could all both more cost-effective and cheaper measurement, while providing more actuate and lower variance carbon estimation area soil carbon assessment. Improving sample analysis time and deploying approaches for proximal sensing of gravel content appear the most realisable improvements, and these will both make a marked reduction in project life measurement costs.

A real opportunity exists to use remote sensing inputs as surrogates or replacements for existing parameters in soil modelling methodologies to greatly improve the spatial resolution and accuracy of modelled approaches which may make them less conservative and more attractive for implementation. In process-based model, model inputs that are typically based on agriculture census datasets can be replaced with time series of remotely sensed datasets (crop/pasture type and land management practices such as fallow period, cover factor). There is an emerging opportunity to fuse datasets of cop/pasture height and high spatial resolution primary and secondary attributes from satellite and UAV remote sensing with carbon models for improved prediction and localisation of parameterisation.

### 9.7.4 Financial proposition and costs and access to capital

A significant part of soil carbon sequestration projects occurs very early in project lifetimes which can represent a barrier to entry. Depending on how payments for sequestration are made this can present a challenging cash flow to participants. As of July 2020, the Clean Energy Regulator can provide a $5000 advance to support to soil method baseline sampling costs. Similarly the new ERF soil carbon method (Soil Carbon (2021) may be helpful in reducing costs.

### 9.7.5 Industry supply chains and skills

The sector is well served by advisers and implementation partners.

### 9.7.6 Market opportunities or market creation

There is significant market interest in projects however farmers and land managers are often unclear on the veracity of the advice they are given by project proponents.

## 9.8 Scaling knowledge gaps:

Currently there is significant focus on innovations aimed at reducing measurement costs associated with validating soil carbon stock changes. While an important part of ensuring the integrity of carbon methodologies and for improving the cost-benefit of soil carbon farming through decrease MRV costs, there are additional gaps in knowledge that hamper efforts to ensure that there are pathways to maximise sequestration through soil carbon storage. These include:

1. reducing uncertainties in the economic sequestration potential through better defining opportunities to increase plant-carbon inputs and to better define risk of reversal, carbon saturation, and rates of decomposition at regionally relevant scales. Reducing uncertainty around these key parameters would act to:
    a) support developments in carbon models used by government and/or aggregators for accounting purposes and;
    b) support the development of tools that enable land managers to set realistic soil carbon targets based on the regional agronomic context, ensuring that entry into carbon markets is based on informed decision making.
2. Improved understanding of where (soil x environment x system) carbon sequestration efforts could be negated by increased nitrous oxide emissions. Developing plant-soil budgeting measures that

indicate when the soils carbon-nitrogen cycling is tightly coupled, or where elemental imbalances lead to inefficient cycling, could better inform tactical nutrient management decisions that minimise production emissions.

3. Improved estimates and modelling of soil carbon change potential under emerging agricultural practices, such as regenerative approaches, strategic deep tillage that overcome subsoil constraints, clay delving or spreading practices, and changing rotational practices associated with growing plant protein demands and use of modern cultivars.
4. Increased efforts to develop incentive programs and frameworks that are not constrained by management practice categorisation but provide the land manager the flexibility to respond to unpredictable climate, economic, and market drivers that maximise the ability to overcome site specific constraints to productivity, maximise plant-carbon returns, and minimise carbon erosion or losses. This will allow the land management community to drive on-farm innovation in a tactical manner that can respond to changing needs.
5. Continued innovation support for the development of new practices that increase soil carbon from clearer understanding of where rotational cropping practices will be most effective, understanding how microbiome management could increase soil carbon and soil function, through to plant modifications that increase the longevity of plant residues.

## 9.9 Chapter References


Aitkenhead, M., D. Donnelly, M. Coull, and R. Gwatkin. 2016. Estimating Soil Properties with a Mobile Phone. Digital Soil Morphometrics:89-110.Baldock, J. A., J. Sanderman, L. M. Macdonald, A. Puccini, B. Hawke, S. Szarvas, and J. McGowan. 2013. Quantifying the allocation of soil organic carbon to biologically significant fractions. Soil Research 51:561-576.

Batlle-Aguilar, J., A. Brovelli, A. Porporato, and D. A. Barry. 2011. Modelling soil carbon and nitrogen cycles during land use change. A review. Agronomy for Sustainable Development 31:251-274.

Bhattarai, T. and McCosker, T. 2019 Construction and testing of the first commercial scale SCANS unit for measuring soil carbon in the Australian red meat industry. Report to MLA pp 49.

Blair, N., R. D. Faulkner, A. R. Till, M. Korschens, and E. Schulz. 2006a. Long-term management impacts on soil C, N and physical fertility - Part II: Bad Lauchstadt static and extreme FYM experiments. Soil & Tillage Research 91:39-47.

Blair, N., R. D. Faulkner, A. R. Till, and P. R. Poulton. 2006b. Long-term management impacts on soil C, N and physical fertility - Part 1: Broadbalk experiment. Soil & Tillage Research 91:30-38.

Bowling, L. C., K. A. Cherkauer, C. I. Lee, J. L. Beckerman, S. Brouder, J. R. Buzan, O. C. Doering, J. S. Dukes, P. D. Ebner, J. R. Frankenberger, B. M. Gramig, E. J. Kladivko, and J. J. Volenec. 2020. Agricultural impacts of climate change in Indiana and potential adaptations. Climatic Change 163:2005-2027.

Chappell, A., J. Sanderman, M. Thomas, A. Read, and C. Leslie. 2012. The dynamics of soil redistribution and the implications for soil organic carbon accounting in agricultural south-eastern Australia. Global Change Biology 18:2081-2088.

Clifford, D., D. Pagendam, J. Baldock, N. Cressie, R. Farquharson, M. Farrell, L. Macdonald, and L. Murray. 2014. Rethinking soil carbon modelling: a stochastic approach to quantify uncertainties. Environmetrics 25:265-278.

DoEE (2019b) National Inventory Report 2017, Volume 2. The Australian Government Submission to the United Nations Framework Convention on Climate Change. Australian National Greenhouse Accounts. April 2018. Department of the Environment and Energy (DoEE), Canberra. https://www.environment.gov.au/climate-change/climate-sciencedata/greenhouse-gas-measurement/publications/national-inventory-report-2017

Donohue, R. J., R. A. Lawes, G. Mata, D. Gobbett, and J. Ouzman. 2018. Towards a national, remote sensing-based model for predicting field-scale crop yield. Field Crops Research 227:79-90.

Eady S., Grundy M., Battaglia M. & Keating B. (2009) An analysis of greenhouse gas mitigation and carbon biosequestration opportunities from rural land use. CSIRO, St Lucia, QLD.

England, J. R., and R. A. V. Rossel. 2018. Proximal sensing for soil carbon accounting. Soil 4:101-122.

Fleming, A., C. Stitzlein, E. Jakku, and S. Fielke. 2019. Missed opportunity? Framing actions around co-benefits for carbon mitigation in Australian agriculture. Land Use Policy 85:230-238.

Fletcher, A. L., C. Chen, N. Ota, R. A. Lawes, and Y. M. Oliver. 2020. Has historic climate change affected the spatial distribution of water-limited wheat yield across Western Australia? Climatic Change 159:347-364.

Guerschman, J. P., and M. J. Hill. 2018. Calibration and validation of the Australian fractional cover product for MODIS collection 6. Remote Sensing Letters 9:696-705.

Hochman, Z., Gobbett, D. and Horan, H. (2017) Climate trends account for stalled wheat yields in Australia since 1990. Global Change Biology 23(5) 2071-2081 https://doi.org/10.1111/gcb.13604

Hutchinson J. J., Campbell C. A. & Desjardins R. L. (2007) Some perspectives on carbon sequestration in agriculture. Agricultural and Forest Meteorology 142, 288-302.

Jackson, R. B., and M. M. Caldwell. 1993. Geostatistical Patterns of Soil Heterogeneity around Individual Perennial Plants. Journal of Ecology 81:683-692.

Janzen, H. H. 2006. The soil carbon dilemma: Shall we hoard it or use it? Soil Biology & Biochemistry 38:419-424.

Karunaratne, S. B., T. F. A. Bishop, J. S. Lessels, J. A. Baldock, and I. O. A. Odeh. 2015. A space-time observation system for soil organic carbon. Soil Research 53:647-661.

Karunaratne SB, Asanopoulos C, Jin HD, Searle S, Macdonald L, Macdonald B (2022) Digiscape Future Science Platform project final report: a novel framework for the estimation of soil organic carbon sequestration deficit in the fine fraction soil associated with the current land management practices. CSIRO, Australia. 18 pp.

Kirkby, C. A., A. E. Richardson, L. J. Wade, G. D. BattenB, C. Blanchard, and J. A. Kirkegaard. (2013) Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biology & Biochemistry 60:77-86.

Lin, L. X., Z. Q. Gao, and X. X. Liu. 2020. Estimation of soil total nitrogen using the synthetic color learning machine (SCLM) method and hyperspectral data. Geoderma 380.

Lobell, D. B., J. M. Deines, and S. Di Tommaso. 2020. Changes in the drought sensitivity of US maize yields. Nature Food 1:729-735.

Luo, Z., Feng, W., Luo, Y., Baldock, J., Wang, E., 2017. Soil organic carbon dynamics jointly controlled by climate, carbon inputs, soil properties and soil carbon fractions. Global Change Biology 23, 4430–4439. https://doi.org/10.1111/gcb.13767

Luo, Z., Wang, E., Sun, O.J., 2010. Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: A review and synthesis. Geoderma 155, 211–223. https://doi.org/10.1016/j.geoderma.2009.12.012

Manzoni, S., and A. Porporato. 2009. Soil carbon and nitrogen mineralization: Theory and models across scales. Soil Biology & Biochemistry 41:1355-1379.

Minasny, B., A. B. McBratney, V. Bellon-Maurel, J. M. Roger, A. Gobrecht, L. Ferrand, and S. Joalland. 2011. Removing the effect of soil moisture from NIR diffuse reflectance spectra for the prediction of soil organic carbon. Geoderma 167-68:118-124.

Ng, W., B. Minasny, and A. McBratney. 2020. Convolutional neural network for soil microplastic contamination screening using infrared spectroscopy. Science of the Total Environment 702.

Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. Scientific Reports 9, 11665.

Padarian, J., B. Minasny, and A. B. McBratney. 2019. Using deep learning for digital soil mapping. Soil 5:79-89.

Padarian, J., B. Minasny, and A. B. Mcbratney. 2020. Machine learning and soil sciences: a review aided by machine learning tools. Soil 6:35-52.

Paustian, K., S. Collier, J. Baldock, R. Burgess, J. Creque, M. DeLonge, J. Dungait, B. Ellert, S. Frank, T. Goddard, B. Govaerts, M. Grundy, M. Henning, R. C. Izaurralde, M. Madaras, B. McConkey, E. Porzig, C. Rice, R. Searle, N. Seavy, R. Skalsky, W. Mulhern, and M. Jahn. 2019. Quantifying carbon for agricultural soil management: from the current status towards a global soil information system. Carbon Management 10:567-587.

Robertson, G. P., K. M. Klingensmith, M. J. Klug, E. A. Paul, J. R. Crum, and B. G. Ellis. 1997. Soil resources, microbial activity, and primary production across an agricultural ecosystem. Ecological Applications 7:158-170.

Roxburgh S. H., England J. R., Evans D., Nolan M., Opie K., Paul K. I., Reeson A., Cook G. & Thomas D. (2020) Potential future supply of carbon offsets in the land sector in Australia, CSIRO Report, 389pp.

Roxburgh, Stephen; Paul, Keryn; Pinkard, Libby. Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF). Canberra: CSIRO; 2020. https://doi.org/10.25919/5f85eb3423299

Sanderman, J., and J. A. Baldock. 2010. Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective. Environmental Research Letters 5.

Sanderman J., Farquharson R. & Baldock J. (2010) Soil carbon sequestration potential: A review for Australian agriculture. p. 81. CSIRO, Urrbrae, S.A.

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proc Natl Acad Sci USA 114, 9575. https://doi.org/10.1073/pnas.1706103114

Sivakumar, M. V. K., and R. Stefanski. 2007. Climate and land degradation - an overview. Climate and Land Degradation:105-+.Doi 10.1007/978-3-540-72438-4_6

Skjemstad, J. O., L. R. Spouncer, B. Cowie, and R. S. Swift. 2004. Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. Australian Journal of Soil Research 42:79-88.

Smith, P. 2005 An overview of the permanence of soil organic carbon stocks: influence of direct human induced, indirect and natural effects, European Jounal of Soil Science 56(5) 673-680 https://doi.org/10.1111/j.1365-2389.2005.00708.x

Rossel, R. A. V., and R. Webster. 2011. Discrimination of Australian soil horizons and classes from their visible-near infrared spectra. European Journal of Soil Science 62:637-647.

Viscarra Rossel, R.A., Webster, R., Bui, E.N., Baldock, J.A., 2014. Baseline map of organic carbon in Australian soil to support national carbon accounting and monitoring under climate change. Global Change Biology 20, 2953–2970. https://doi.org/10.1111/gcb.12569

Waldner, F., and F. I. Diakogiannis. 2020. Deep learning on edge: Extracting field boundaries from satellite images with a convolutional neural network. Remote Sensing of Environment 245.

WALKLEY, A.; BLACK, I. ARMSTRONG. AN EXAMINATION OF THE DEGTJAREFF METHOD FOR DETERMINING SOIL ORGANIC MATTER, AND A PROPOSED MODIFICATION OF THE CHROMIC ACID TITRATION METHOD. Soil Science: January 1934 - Volume 37 - Issue 1 - p 29-38

Wang, D. & Anderson, D.W. (1998) Direct measurement of organic carbon content in soils by the Leco CR-12 carbon analyzer, Communications in Soil Science and Plant Analysis, 29:1-2, 15-21, DOI: 10.1080/00103629809369925

Wang, W. J., C. J. Smith, and D. Chen. 2004. Predicting soil nitrogen mineralization dynamics with a modified double exponential model. Soil Science Society of America Journal 68:1256-1265.

Wijesingha, J., T. Moeckel, F. Hensgen, and M. Wachendorf. 2019. Evaluation of 3D point cloud-based models for the prediction of grassland biomass. International Journal of Applied Earth Observation and Geoinformation 78:352-359.

Weiss, M., B. van den Hurk, R. Haarsma, and W. Hazeleger. 2012. Impact of vegetation variability on potential predictability and skill of EC-Earth simulations. Climate Dynamics 39:2733-2746.

Weiss, M., F. Jacob, and G. Duveiller. 2020. Remote sensing for agricultural applications: A meta-review. Remote Sensing of Environment 236.

Whitbread, A. M., G. J. Blair, and R. D. B. Lefroy. 2000. Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia 1. The effects on wheat yields and nutrient balances. Soil & Tillage Research 54:63-75.

Wimalathunge, N. S., and T. F. A. Bishop. 2019. A space-time observation system for soil moisture in agricultural landscapes. Geoderma 344:1-13.

Yeboah, S., E. O. Danquah, P. Oteng-Darko, K. Agyeman, and E. N. Tetteh. 2021. Carbon Smart Strategies for Enhanced Food System Resilience Under a Changing Climate. Frontiers in Sustainable Food Systems 5.

Zhao, L. Y., F. Waldner, P. Scarth, B. Mack, and Z. Hochman. 2020. Combining Fractional Cover Images with One-Class Classifiers Enables Near Real-Time Monitoring of Fallows in the Northern Grains Region of Australia. Remote Sensing 12.

# 10 Blue and Teal Carbon

| | | |
|---|---|---|
| **Emission Type** | Avoided | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Figure 110-1: Blue and teal carbon technology type**

## 10.1 Summary

**Description and current uptake**

Blue carbon describes the potential carbon storage and sequestration of vegetated coastal ecosystems (VCEs), including mangrove, saltmarsh, suptatidal forests and seagrass ecosystems. Teal carbon relates to carbon stored in inland freshwater wetlands. Organic carbon sequestration in these ecosystems occurs in the biomass of the plants and the soil (sediment) in which they grow. Blue and teal carbon ecosystems store more carbon on average than most terrestrial ecosystems and typically sequester carbon at faster rates. Nationally it is estimated that mangroves and saltmarsh together sequester annually about 11.0 Mt $CO_2$-e per ha per year, and seagrass a further 4.9–5.6 per ha per year. There are no estimates for freshwater wetlands at present.

Methods to characterize sequestration for blue carbon ecosystems depend on management activities that either prevent greenhouse gas (GHG) emissions or increase overall carbon accumulation. Australia's Emissions Reduction Fund (ERF) has one eligible blue carbon method, and none have yet been approved for teal carbon. The *Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022* is based on the (re)introduction of tidal flows to land where tides have been previously excluded. This can increase carbon sequestration through the carbon accumulation in vegetation and soils and decrease GHG emissions from prior land-uses.

**Sequestration potential**

There are no reliable estimates of the national sequestration – technical potential or Economic potential – with restoration of blue and teal carbon ecosystems in Australia. The best estimate of potential sequestration is from Serrano et al., (2019) of 3-4Mt $CO_2$-e per year. There is a need for better mapping of the areal extent of blue and teal carbon habitat types, national models of inundation and delineation of feasible areas or where management actions include better conservation restoration with tidal introduction, or other management activities might be employed to achieve GHG sequestration.

Several regional projects around in Australia demonstrate that emissions reduction strategies, such as tidal introduction, can yield substantial net sequestration though the relative balance of avoided emissions and reductions can often vary according to local circumstances. For example, in the Yandina Wetlands Restoration Project (part of the Sunshine Coast's Blue Heart initiative), sequestration of 18.5 t $CO_2$-e per ha per year was achieved when sugarcane land transitioned to supratidal forests and 6.2 t $CO_2$-e per ha per year when transitioned to saltmarshes. In the Great Barrier Reef Region, it was found that tidal reintroduction in catchments of the Wet Tropics could feasibly abate annually 0.22 Mt $CO_2$-e and 0.16 Mt $CO_2$-e in Fitzroy Basin catchments.

**Technology readiness potential and commercial readiness**

Technologies for tidal reintroduction and VCE restoration are well established but t relatively high capital and other upfront costs can be a barrier. For example, tidal reintroduction includes hydrological modelling, modification or removal of tidal barriers and ongoing monitoring, reporting and verification (MRV). Some restoration projects have ready high-level commercial readiness as they are already established and are seeking ERF accreditation for either new areas to restore or to make other improvements that would be considered additional under the method. Other sites have a low level of commercial readiness, constrained by up-front project development costs.

**Scalability, length of storage, measurement and verification**

Projects in coastal wetlands face several challenges, including relatively high implementation costs, complexity of legal rights in the coastal zone, and uncertainties related to ecological processes and climate change. The sequestration storage length of blue and teal carbon sequestration is less susceptible to some risks that land-based ecosystems are prone to, such as fire. However, there are risks associated with climate change and severe weather events. Costs associated with in situ monitoring and verification requirements are considered a significant impediment to blue carbon tidal projects. Modelling approaches are being developed for assessing carbon sequestration and hydrological connectivity that should make these costs more feasible.

**Social, environmental impacts, risks and co-benefits**

Blue carbon ecosystems provide multiple co-benefits, including fisheries production, pollutant removal and coastal protection, and are culturally important to Indigenous people. Coastal restoration can deliver social and economic benefits, including support of livelihoods and enhanced delivery of ecosystem services. Landholders can benefit from converting marginal agricultural land to blue or teal carbon sequestration activities – although there is an associated risk of limiting future land management options. Blue and teal carbon ecosystems are subject to external stressors (such as cyclones, sea-level rise, changes in precipitation), which may undermine their ability to provide ecosystem services and maintain carbon sequestration potential.

**Barriers to implementation**

The principal factors influencing the opportunity for coastal wetland restoration vary across Australia's coastline. There is variation in land use, level of carbon sequestration that could be achieved and laws and policies regulating land-use change and land ownership.

Costs for blue and teal carbon projects can vary considerably depending on the type of ecosystem being managed, the restoration methods used, and costs of establishment and ongoing maintenance and meeting monitoring, reporting, and verification requirements. There is considerable interest from the private sector in investing in blue carbon projects. Motivation for this ranges from meeting corporate stewardship responsibilities to seeking environmental offsets for business activities.

**Scaling knowledge gaps**

To effectively scale the sequestration potential of blue and teal carbon ecosystems requires better quantification and tools to understand where the feasible areas to undertake projects are, and what are the life cycle costs that will make them viable.  Key knowledge gaps in carbon sequestration potential of other lesser-understood blue carbon habitats such as seagrass and kelp and the potentially significant sequestration potential of teal ecosystems require systematic investment.

Understanding the opportunities for Indigenous engagement in blue and carbon research will lead to multiple co-benefits but requires a comprehensive engagement strategy.

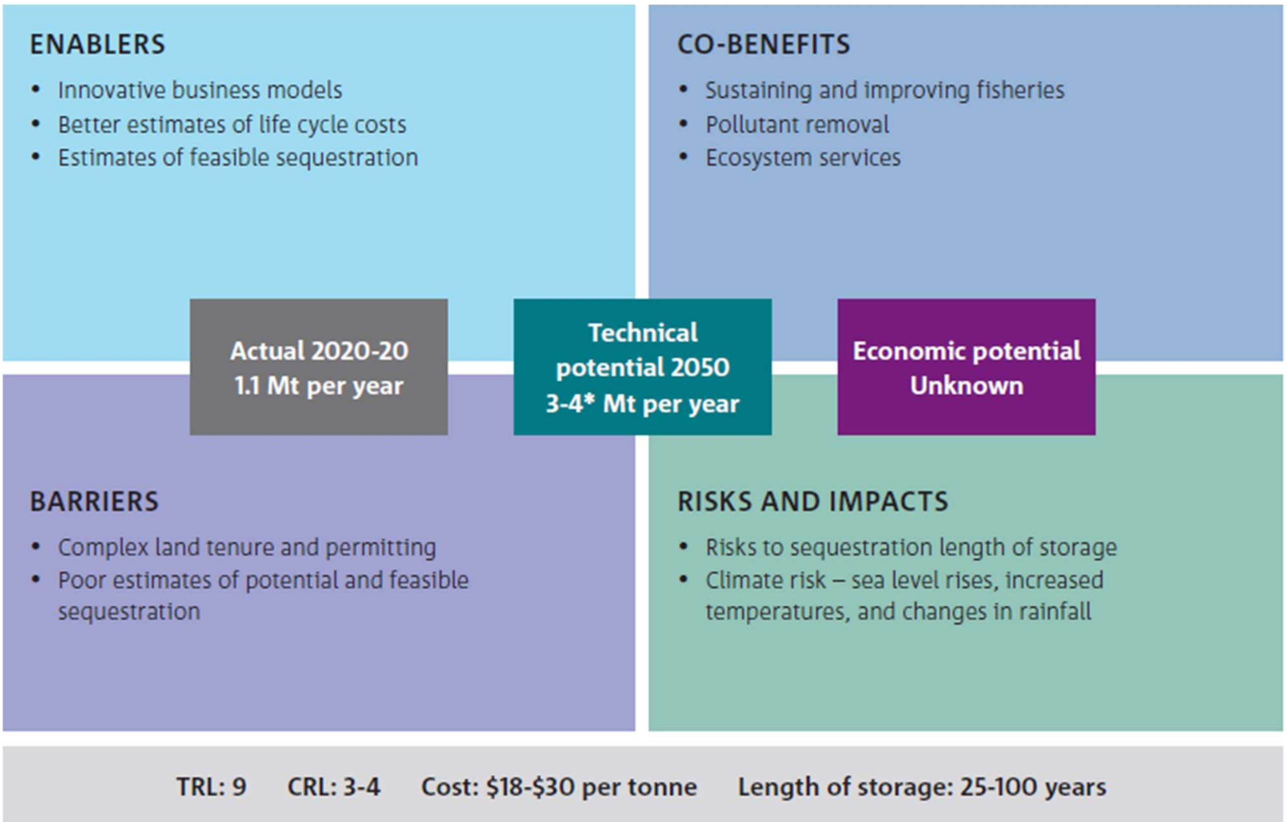



**Figure 10-1: Summary of blue carbon technology. *From Serrano et al 2019, assuming 10% restoration and 100% avoidance. Actual sequestration reflects sequestration in Blue carbon - mangroves over the period 2010-2020, as reported in Australia's annual national greenhouse gas inventory. Actual sequestration includes soil carbon as well as living biomass, debris and soil.**

## 10.2 Description and current uptake

*Blue carbon* is a term coined in 2009 to describe the ability of coastal wetlands including mangroves forests, saltmarshes (or tidal marsh), seagrass meadows and tidally influenced floodplain forests (dominated by *Melaleuca* and *Casuarina* species) to sequester high concentrations of carbon dioxide in their soils and biomass. These coastal wetlands form interconnected and dynamic mosaics; saltmarshes and mangroves occur in the upper intertidal zone, supratidal forests can occur landward and are often interspersed with mangrove, while seagrass meadows extend across the lower intertidal zone to subtidal depths[28].

*Teal carbon*, which has only recently entered the carbon colour nomenclature, refers to the carbon stored in freshwater wetlands and includes surface waters – whether natural, modified, or artificial – that are

[28] Kelp occurs abundantly around Australia (3.5–7.1 Mha) but is not formally recognised as blue carbon because the permanence sequestered carbon is yet to be demonstrated and quantified (Hill et al., 2016; Filbee-Dexter and Wernberg, 2020). Kelp, and other seaweeds can also be used indirectly as a feedstock for other net emission technologies (NETs), such as BECCS (see chapter 13), as well as in the production of biofuels and other high-value products (e.g., pharmaceuticals).

subject to permanent, periodic, or intermittent inundation. They may be broadly classified as *riverine* (having an open channel), *lacustrine* (large open water systems such as lakes) or *palustrine* (small vegetated non-channel environments including billabongs, swamps, bogs, and springs) wetlands.

As with terrestrial forests, organic carbon sequestration in these coastal and freshwater wetlands occurs in the above- and below-ground biomass of the plants, and in the soil (often termed sediment when applied to aquatic ecosystems) in which they grow. The organic carbon in the soil can be acquired by the plants themselves through photosynthesis (autochthonous), or it can originate elsewhere, transported into the ecosystem by water or wind (allochthonous). Typically, the soil stores more organic carbon than the biomass of the plants; around 90% in saltmarshes and seagrasses and 75% in mangroves (Alongi 2014). Blue and teal carbon ecosystems store more carbon per unit area than most terrestrial ecosystems, and typically sequester carbon at faster rates (McLeod et al., 2011). This is possible because the water which saturates the soil reduces oxygen concentrations, creating anoxic conditions that slow rates of decomposition and leads to the accumulation of organic matter. In tidally inundated coastal wetlands the salinity present reduces the amount of methane produced (Al-Haj and Fulweiler 2020), but in teal carbon ecosystems methane production can be high, and their effectiveness for GHG abatement requires further research (Arias-Ortiz et al., 2021).

In Australia from about 1830 massive areas of coastal and freshwater wetlands – over 70% in some southern states – were cleared to make way for agricultural development and drainage for flood protection. Land reclamation through tidal restriction (e.g., sea walls, bund, drain) of coastal waterways diminished the landward extent of mangrove and saltmarsh, while water resource developments, primarily the building of dams, diversion of water and development of floodplains, significantly reduced the extent and condition of freshwater wetlands. This resulted not only in large-scale and rapid GHG emissions but also diminished their sequestration potential. While contemporary (from about 1990) clearing of these wetlands is now significantly lower (~0.01-0.03 % $yr^{-1}$) than historical rates, ongoing agricultural, urban, and coastal development, and a legacy of cumulative impacts from poor land-use practices further compromise the extent, condition, and carbon sequestration potential of these wetlands (Rogers et al., 2016).

Coastal wetlands are formally recognised within Australia's national greenhouse gas accounting guidelines, under the Land Use, Land Use Change and Forestry (LULUCF) sector. Mangroves meet Australia's definition of forests and estimates of emissions and removals from mangroves are respectively reported under the sub-sectors *forests converted to settlements* and *wetlands converted to forests in the* Australian Government Emission Inventory System (AGEIS). Tidal marshes and seagrass meadows are reported as subdivisions under *wetlands remaining wetlands* and *forest land converted to wetlands*. The recently released National Ocean Account, Experimental Estimates (ABS 2022) also provides national carbon stock and sequestration assessments of mangroves and seagrasses.

As with terrestrial ecosystems, sequestration methods for blue and teal carbon ecosystems depend on recognised management practices that either: (1) prevent an activity that would otherwise cause greenhouse gas emissions (termed *avoidance*), such as preventing vegetation clearing or threats that impair habitat condition, or (2) lead to an increase in overall carbon accumulation through either direct *restoration* (e.g., planting, seed dispersal) or indirectly, for example through the re-introduction of tidal hydrology, or improved land management practices such as grazing exclusion of feral animals. Kelleway et al., (2019, 2021) documented and analysed for the Australian Government he sequestration potential of several proposed management activities encompassing both avoidance and indirect and active restoration. They found that on a per area basis, (re)introduction of tidal flow resulting in the establishment of mangrove and tidal marsh led to the highest sequestration of organic carbon.

Subsequently, the first accredited Emissions Reduction Fund (ERF) method for blue carbon— *Carbon Credits (Carbon Farming Initiative – Tidal Restoration of Blue Carbon Ecosystems) Methodology Determination 2022,* hereafter the blue carbon tidal method) was developed and released in 2022. The basis for the tidal method is that the (re)introduction of tidal flows, by removal or modification of tidal flow restriction devices, results in the rewetting of previously drained coastal wetland ecosystems, that over time can lead to sequestration by both decreasing (termed avoidance) emissions of methane and nitrous oxide, and by increasing carbon sequestration (termed removals) by promoting the growth of mangroves, saltmarsh, and supratidal forests (but not seagrass). Sequestration is assessed relative to emissions and removals of the landuse prior to tidal introduction (termed the baseline) and determines the number of Australian Carbon Credit Units (ACCUs) that can be sold (Lovelock et al., 2021,2022). A regional model, BlueCAM, aligned with the national GHG guidelines and using the best available Australian data, has been developed to assist prospective projects implementing the blue carbon tidal method to estimate and track sequestration from carbon sequestered in soils and biomass and avoided emissions from alternative land uses (Lovelock et al. 2022). To date, several projects are seeking accreditation for the blue carbon tidal method but given the time to establish the restoration and realise the carbon sequestration this is like to be several years before ACCUs are produced.

Other sequestration methods are being considered for possible inclusion in the ERF including excluding feral and domestic ungulates from coastal and freshwater wetlands to avoid disturbance and grazing, and the scaling up of seagrass restoration methods (see section 10.5). In addition to the ERF, several international voluntary carbon standards have blue carbon methods that accredit eligible offsets under Australia's Climate Active Certification. The Verified Carbon Standard has multiple methods, including for tidal wetland and seagrass restoration (VM0033), and avoiding unplanned wetland loss or degradation (VM0007). Plan Vivo's Standard V5 and Gold Standard both have methods for afforestation/reforestation and sustainable management of mangroves. None of these methods has yet been applied in Australia.

The ability to apply tier 2 and 3 GHG sequestration and emission values to both National Emissions inventory reporting of blue carbon habitats, and in the BlueCAM model, have been supported by studies from around Australia that were initially collated under the CSIRO-led Carbon Cluster program (Serrano et al., 2019). Subsequent studies by Australian researchers have further documented patterns of, carbon stocks, GHG sequestration and emission rates, in relation to various local, regional, historical, climate and anthropogenic factors, that globally represent one of the most detailed compendiums of blue carbon data available (Costa and McCreadie 2022). However, data on methane fluxes from coastal wetlands in Australia remains limited, and IPCC default emission factors are relied upon. In teal habitats, there hasn't been a similar level research, and as a result sequestration and emissions rates are much less resolved, with only a few studies in southeast Australia (Carnell et al., 2018).

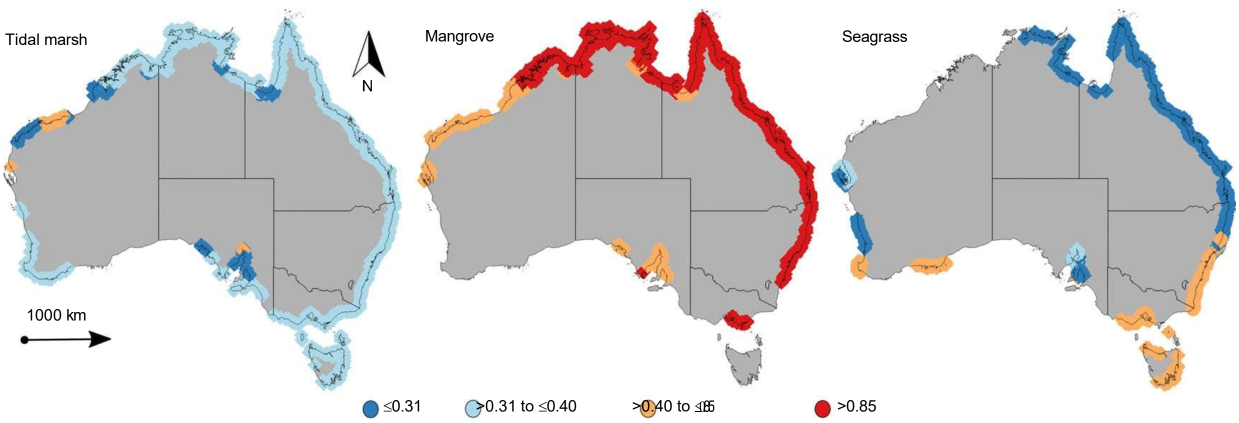


Figure 110-2: Soil carbon sequestration rates (Mg C $ha^{-1}$ $year^{-1}$) in tidal marshes, mangroves and seagrass across Australian climate regions. The four ranges of data (indicated by different colours) are based on the lower quartile, median quartile, and upper quartile of available data. From Serrano et al (2019).

## 10.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt.yr $^{1}$) | Key evidence |
|---|---|---|
| **Technical Potential** | | |
| *Avoided* | 2.1-3.1 | Serrano et al., (2019) – estimates of current VCE losses. |
| *Restoration* | 1.15 | Serrano et al., (2019) – Restoration on 10% of damaged VCE's |
| **Economic potential by 2025** | | |
| | | |
| **Economic potential by 2035** | | |
| **Economic potential by 2050** | | |

Table 110-2: Best estimates of blue and teal carbon sequestration potential

While there are now reasonably good area-based estimates for carbon accumulation and GHG emission rates of different coastal wetlands across Australia's region there are no reliable estimates of the national carbon sequestration – technical potential or Economic potential – for blue and teal carbon in Australia. Even with the release of ERF tidal restoration method, and the regionally based Blue CAM model (Lovelock et al., 2021), there is no accompanying national estimate of what sequestration this method could potentially, or feasibly, yield.

Such national sequestration estimates require improved mapping of the areal extent and assessment of changes that are occurring in these blue and teal carbon habitats. While mangroves have been systematically mapped with remote sensing since 1988 the national extent of saltmarsh and seagrass are only estimates derived mainly from the aggregation of state-based data. Systematic mapping of these habitats is however underway as part of the National Ocean Account, Experimental Estimates with assessments of saltmarsh and kelp anticipated for release in November 2022. These national accounts are also reporting the magnitude and change in carbon storage and sequestration of these coastal wetlands, providing a useful baseline from which to estimate technical potential and Economic potential sequestration; however they can't presently discriminate whether they are the result of management interventions, or the consequence of natural processes.

### Technical Potential sequestration

In assessing the biophysical potential of blue and teal ecosystems to achieve GHG sequestration the regional variation in the extent, composition, biomass, and productivity, of different coastal and freshwater wetlands habitats must be considered. Below, contemporary national extent and carbon sequestration, and known emissions for these wetlands are summarised:

- *Mangroves* have been systematically mapped with remote sensing since 1988 the carbon sequestration potential of mangroves is the best quantified of any blue and teal ecosystems (Lymburner et al., 2021). Nationally mangroves occupy about 1 million hectares (Mha) and occur mainly in tropical regions (73%) and are naturally latitudinally limited in their southerly distribution. From 2020 to 2021, mangrove extent increased by 2.3% (0.023 Mha) to 1.07 MHa. In 2021 mangroves nationally stored 260 Mt $CO_2$-e and sequestered and estimated 8.6 Mt $CO_2e$ per annum (ABS 2022). Emissions from clearance of mangroves under the *forest to settlement* category in the AGEIS were 21 Mt $CO_2$-e and show a year-on-year decline over the last decade (103 Mt $CO_2$-e in 2010) that are the result of reduced rates of mangrove clearing. These are presumably from enforcement of stricter development regulations being enforced and suggest there only relatively modest sequestration can be achieved (Commonwealth of Australia 2021).

- *Saltmarsh* are estimated to occupy 1.37 -1.5 Mha occurring mainly in tropical regions (Queensland, 39%; the Northern Territory, 37%; Western Australia, 22%) and in temperate regions today they are much reduced in extent from historical drainage land clearing and conversion. Detailed mapping and estimation of carbon stocks and sequestration in saltmarsh is expected to be released in November 2022. Saltmarsh along with small mangroves and freshwater wetlands are considered generically under the *wetlands to settlements* sub-category of AGEIS. Progressive reductions in emissions are reported to have occurred over the last decade from 75 Mt $CO_2$-e in 2010 to 9 Mt $CO_2$-e in 2019 (Commonwealth of Australia 2021).
- *Teal wetlands* occupy 33.9 Mha and are dominated by palustrine (18.2 Mha, 61%) and lacustrine (10.2 Mha, 34%) habitats. These freshwater wetlands occur mainly in northern Australia, with Queensland alone representing almost a third (32%) of Australia's freshwater wetlands, and in large temperate drainage divisions including Lake Eyre (25%) and the Murray Darling (16%) basin (Bino et al., 2016). Today, artificially constructed freshwater storage areas (e.g., dams, reservoirs, farm ponds) occupy a significant area (0.69 Mha) of the national estate (Bino et al., 2016). First-order national sequestration rates in the dominant (about 84%) palustrine and lacustrine habitats of teal carbon ecosystems are respectively 125.4 and 70.7 Mt $CO_2$-e $year^{-1,}$ which in aggregate give a baseline of about 196 Mt $CO_2$-e $year^{-1}$. The only comprehensive survey of potential GHG sequestration is across Victoria's ~ 5,000 temperate, alpine, and semi-arid wetlands (2370 Mha) where annual carbon sequestration is estimated to be 3 Mt $CO_2$-e (Carnell et al., 2021). Historically, drainage and loss of ~260 Mha of wetlands since European settlement (~1834) is calculated to have released between 20 and 75 Mt $CO_2$-e.
- *Seagrasses* are estimated to cover between 2.56 to 3.06 Mha and are distributed across subtropical (38%), tropical (32%), and arid (16%) regions of Australia, with more than two-thirds located in state waters (notably South Australia) and a further one-third located in Commonwealth waters, mainly in the Torres Strait. in 2021 between 289 and 341 Mt $CO_{2-}$e were stored in seagrass meadows which sequestered 4.9 to 5.6 Mt $CO_{2-}$e (ABS 2022). However, given the large but unreliable estimates of seagrass areal extent, Discrepancies in national estimates of seagrass carbon storage and sequestration reported in various studies stem from assumptions made as to the extent of seagrass: a seagrass extent of 9.3–12.8 Mh used by Serrano et al., (2018) and subsequently Young et al., (2021) included recently discovered deep-water seagrass and is 3–4 times greater than the 2.6–3.1 Mha reported by the National Ocean Accounts (ABS 2022) .

In summary, the distribution of coastal and freshwater wetlands in Australia are mainly in Northern Australia and consequently Queensland, Northern Territory, and Western Australia may have greater sequestration potentially sequestration potential than – apart from South Australia– many of the southern states (Figure 10-3).

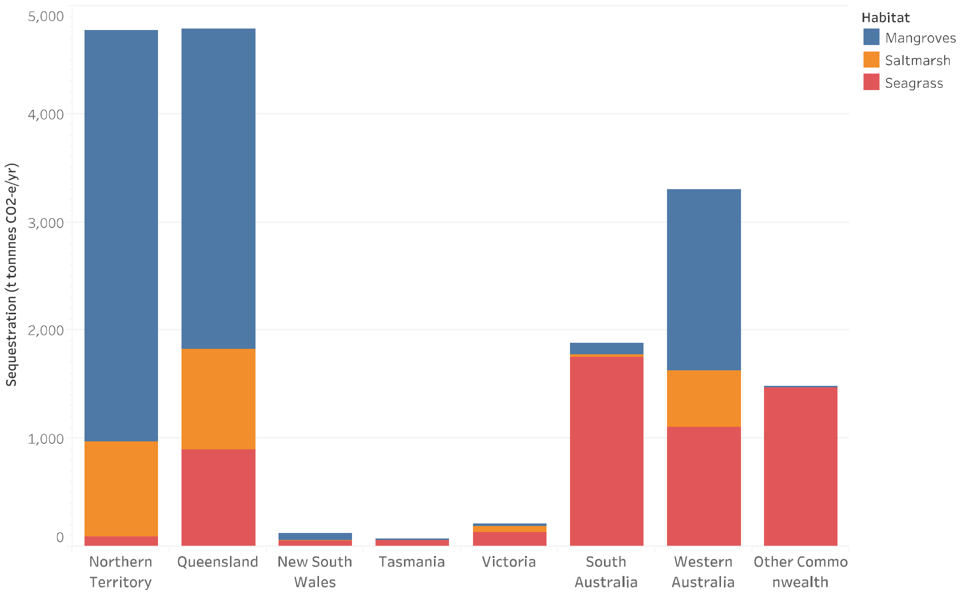



**Figure 110-3. Soil carbon sequestration rates (thousands tonnes $CO_2$-e ha$^{-1}$ yr$^{-1}$) in tidal marshes, mangroves and seagrass across Australian states, territories and Commonwealth waters.**

In further refining what potential sequestration could be achieved in these wetlands from avoidance or restoration methods the historical loss of these habitats from drainage and land-clearing, although poorly documented, is a commonly used proxy for assessing potential sequestration and assumes that because these habitats previously occurred, they can – with the right methods and conditions – be restored.  In the first national assessment of blue carbon in Australia, Serrano et al., (2019) estimated that greenhouse gas emissions equivalent to 2.1-3.1 Mt $CO_2$-e year$^{-1}$ had resulted from historical clearing and degradation of blue carbon ecosystems. It was also estimated that restoring 10% of cleared blue carbon ecosystems in Australia (0.57 Mha) would generate 1.15 Mt $CO_2$-e year$^{-1}$ of sequestration in soil alone. While these are the values have been adopted for this report (Table 11.2) as the range of in potential sequestration , they must be treated with caution as they are generated from (a) uncertain estimates of the areal extent of coastal  habitats and of the rates of historical clearing (Rogers et al., 2016); (b) poor knowledge of the rate and magnitude of emissions that occur, (c) sequestration rates from soil cores of varying lengths extrapolated to 1-metre. Even the scale of assumed restoration seems daunting in terms of the absolute spatial scale, land tenure and technological constraints and the decadal timeframes over which carbon accumulation could be realised.

In relation to assessing the national potential of the tidal re-introduction methods, simple bathtub models that calculate the highest astronomical tide (HAT), and sometimes include sea level rise (SLR) projections (often assumed to be 0.7-1.0 m by 2100), have been applied in several regional studies to predict changes in ecosystem extent and sequestration potential. For example, in Queensland:

- Across the Great Barrier Reef (GBR) region Costa et al., (2022) used the INVEST models and found that by restoring tidal exchange in 0.9 Mha within the GBR catchments, restoration could sequester an additional ~0.8 Mt $CO_2$-e by the end of the twenty-five-year crediting period.
- it is estimated (based on land drained for sugarcane and it current distribution and its elevation on the flood plain,) that between 66,000 – 230,000 ha could be used by projects using the tidal blue carbon method (Lovelock unpub.)
- In the Fitzroy catchment, Hagger et a, (2022b) identified 31,686 ha that could be suitable for hydrological restoration to coastal wetlands. With the prediction of a +0.7 m or +1 m sea-level rise, this increased to 60,142 ha or 67,097 ha, respectively.

However, these studies have been hindered by generally poor quality of coastal elevation data for much of the coast, limited spatial resolution of land use data, and inconsistent and incomplete data on the presence of tidal barriers.

National hydrological models that can assess the extent and frequency of inundation of coastal and habitats and improved delineation of the areal extent over which management interventions may feasibly operate are required. The CSIRO, with BHP, is currently undertaking a national blue carbon project that will develop some of this national hydrological capability which should be available in mid 2023. Preliminary modelling results for southeast Australia (NSW, VIC, SA) indicate the area that could be inundated under present sea level conditions is 15,600 ha resulting in an increase of 5600 ha of mangrove and about 10,000 ha of saltmarsh. Total carbon sequestration over 25 years from inundation of cropping, grazing and other agriculture is estimated to be about 2 Mt $CO_2$-e with the more that 50% of this sequestration occurring in Victoria from transitioning grazing lands.

Future (nominally 2050, 2100) climate conditions must also be taken into consideration. Over the coming century, projected sea level rise (SLR) is predicted to inundate low-lying coastal land across Australia leading to landward migration of mangroves, saltmarsh, and to a lesser extent seagrass, increasing their extent by 5–15% (0.38 – 0.92 Mha) under RCP 4.5 or 9–25% (0.45 – 1.06 Mha) under RCP 8.5; Whitt et al. subm.). While the Northern Territory has the largest area available to accommodate coastal wetland migration by 2050 under by 2100 NSW and Victoria are expected to have greater potential to increase state-wide coastal wetland extents and this will also affect their rates of carbon sequestration and accumulation (Young et al., 2021). In GBR studies of potential tidal reintroduction (Costa et al., 2021, 2022; Hagger et al., 2022a, b) projected increases in SLR to 2100 were estimated to significantly increase (by up to 90%) the carbon sequestration that would be achieved by tidal re-introduction alone.

Climate events such as droughts, floods, heatwaves, cyclones, and storms can result in significant actual and future-potential carbon losses. For example, marine heatwaves resulted in large-scale dieback of around 10,000 ha of mangroves in northern Australia's Gulf of Carpentaria (Duke et al., 2017) and the loss of more than 1100 ha of seagrass in Shark Bay, Western Australia, in 2010 is estimated to have resulted in the loss of 2.0–9.0 Mt $CO_2$-e (Arias-Ortiz et al., 2018). As such they can have significant effect on year-to-year national emissions, but they also offer the potential for significant facilitated and active restoration.

**Economic potential**

Several large-scale regional projects in Australia) demonstrate that emissions reductions strategies such as tidal introduction can yield substantial net sequestration (avoided emission). The models of Hagger et al., (2022a, b) provide the best practice feasibility assessments using a multi-stage approach considering stakeholder engagement, biophysical suitability, carbon sequestration, economic feasibility, and the provision of co-benefits for biodiversity, fisheries, water quality, and coastal protection, as well as cultural benefits. Within the Wet Tropics region of the GBR, 5,046 ha of historically cleared coastal wetlands on sugarcane and grazing land were identified that if tidal flows were reinstated around 0.22 Mt $CO_2$-e $yr^{-1}$ could be abated; 58% would be from carbon sequestration in vegetation and soils and 42% from avoided emissions associated with conversion of the land use. Cost-benefit analysis over 25 years demonstrates that at a carbon price of $25 per tonne $CO_2$-e) over 90% of the area would be profitable under conventional farm management practice (Hagger et al., 2022a). In the Fitzroy catchment, the presence of threatened species, the Capricorn Yellow Chat, reduced the land area deemed suitable for restoration from an initial 31,686 ha identified as suitable for hydrological restoration to coastal wetlands to just 13,874 ha. This land area could feasibly abate 0.16 Mt $CO_2$-e per annum, of which 61% would be from carbon sequestration in biomass and soils of restored wetlands and 39% from conversion of the grazing land use. At a carbon price of AUD $40 per tonne $CO_2$-e, tidal restoration over a 25-year crediting period was considered feasible for 51% (7117 ha) of the potential area (Hagger et al., 2022b). But in temperate Western Australia, in the Peel Harvey catchment, only 348 ha of potential and holdings were identified and would abate much less carbon per year (0.004 Mt $CO_2$-e $yr^{-1}$). However, none of the sites would be profitable, even when using the higher carbon price, and this was due primarily to the initial restoration and maintenance costs in the first five years, and because the sites are small with low carbon sequestration per site and poor economies of scale (Hagger et al., 2022b).

The Yandina Wetlands Restoration Project on the Sunshine Coast, Queensland, is the only known study demonstrating realistic sequestration (se case study 1). In 12 years since reinstatement of tidal inundation carbon sequestration of 18.5 t CO2-e $ha^{-1}$ $yr^{-1}$ was achieved when sugarcane land transitioned to supratidal forests, 11.0 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ when the land transitioned to mangroves, and 6.2 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ when the land transitioned to saltmarsh (Iram et al., 2021).

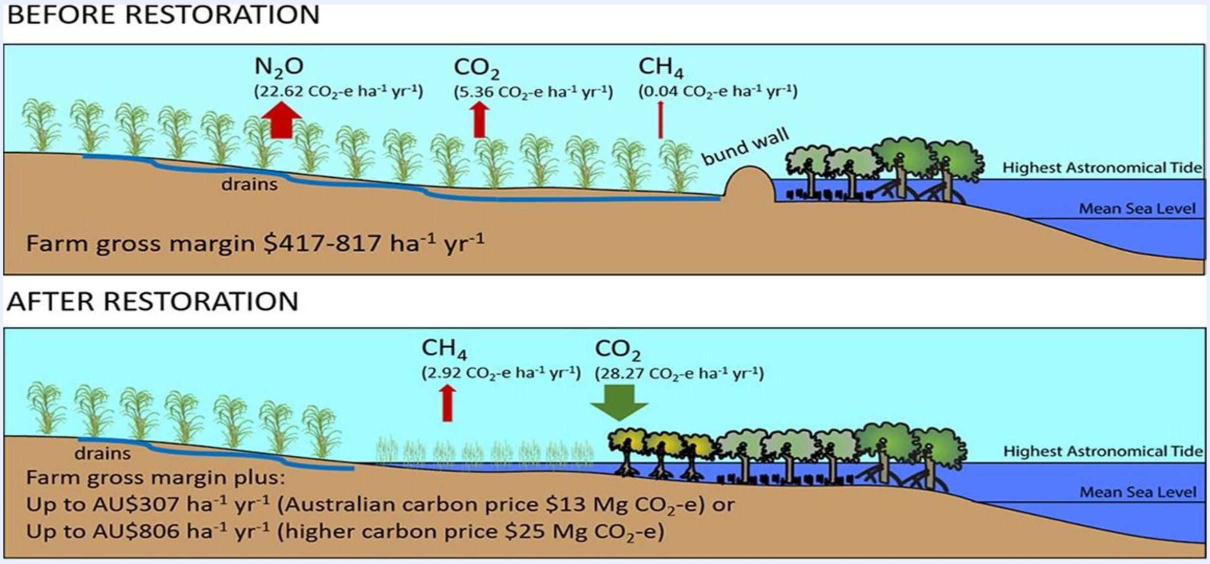
A couple of studies have also started to look at the technical potential and economic feasible sequestration from the exclusion of feral and domestic ungulates. In the Ord Catchment WA, Hagger et al., (2022b) 24,123 ha of land was identified as potentially restorable and though not eligible under the blue carbon tidal restoration method, a conservative (0.3 $CO_2$-e ha $yr^{-1}$) estimate of 7,237 Mg $CO_2$-e $yr^{-1}$ in avoided emissions from reduced grazing pressure could be abated if a method that allows restoration of degraded natural wetlands was developed. In freshwater wetlands in the Wimmera region of Victoria (~7 Mha) exclusion of grazers was estimated to increase above-ground biomass and soil carbon stock by 0.55 Mt C and could reduce emissions by 0.78 Mt $CO_2$-e $yr^{-1}$ (Limpert et al., 2021).

In summary, Table 10-2 highlights the regional variability and some of the factors (e.g., variation in tidal range, land-uses, hydrological modifications of the landscape, biodiversity and the presence of threatened species) that may influence whether sequestration is feasible. Other factors, including current land-use, tenure, and the regulatory environment vary regionally an significantly influence the results of cost-benefit analyses (see table 10-2 and case studies 1 and 2).

**Table 110-2. Economic potential sequestration for blue carbon project over 10, 25 and 30 years.**

| Sequestration Method | Economic Sequestration (Mt $CO_2$ e) | | | Annual average | Area (tHa) |
|---|---|---|---|---|---|
| | 2050 (30 y) | 2030 (10y) | 2045 (25y) | (Mt $CO_2$ e $yr^{1}$) | |
| **Tidal Inundation** | | | | | |
| **Queensland** | | | | | |
| Whole GBR (Costa et al 2022) | 8.8816 | 3.1720 | 7.9300 | 0.32 | 900 |
| Wet Tropics (Hagger et. al 2022a) | 6.1882 | 2.2101 | 5.5252 | 0.22 | 5.046 |
| Fitzroy Catchment (Hagger et al 2022b) | 4.5410 | 1.6218 | 4.0545 | 0.16 | 13.874 |
| **South East Australia** | | | | | |
| New South Wales (CSIRO unpub.) | | | 0.28 | 0.01 | 1.906 |
| Victoria (CSIRO unpub.) | | | 1.1 | 0.04 | 10.521 |
| South Australia (CSIRO unpub.) | | | 0.51 | 0.02 | 3.174 |
| **Western Australia** Peel Harvey (Hagger et al 2022b) | 0.1207 | 0.0431 | 0.1078 | 0.004 | 1.762 |
| **Exclusion of Grazing** | | | | | |
| Ord Catchment (Hagger et al 2022b) | 0.2026 | 0.0724 | 0.1809 | 0.007 | 24.123 |
| Wimmera Catchment (Limpert et al 2021) | | | 19.5 | 0.78 | 7000 |

**Case Study 1: Tidal Reinstatement in Sugar cane lands of the GBR Wet Tropics** (Hagger et al., 2022a)
Average greenhouse emissions from sugar cane cropping ($CO_2$ from soil carbon loss, $N_2O$ from fertiliser N mineralisation and leaching, and $CH_4$ from flooded drains and burning) and removals and emissions after coastal wetland restoration from reinstatement of tidal flows ($CO_2$ removals in aboveground biomass and soil carbon and CH4 emission from brackish water flooding.




**Case Study 2:** ***Yandina Wetlands Restoration Project (***Iram et al., 2021).
The Yandina Wetlands Restoration Project is part of the Blue Heart initiative that aims to restore and protect ~5000 ha wetlands on the Sunshine Coast, mainly to manage flooding, but also to improve water quality, enhance carbon sequestration, increase biodiversity, and provide recreational opportunities. The site was originally a supratidal forest composed of *Melaleuca* spp. that was cleared and drained in the 1990s for sugarcane production. In 2010, tidal inundation was reinstated, and a mosaic of coastal vegetation (tidal marshes, mangroves, and supratidal forests) emerged. Carbon abatement of 18.5 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ was achieved when sugarcane land transitioned to supratidal forests, 11.0 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ when the land transitioned to mangroves, and 6.2 t $CO_2$-e $ha^{-1}$ $yr^{-1}$ when the land transitioned to saltmarshes. Carbon abatement was due to tree growth, soil accumulation, and reduced $N_2O$ emissions due to the cessation of fertilization. Coastal wetland restoration in this subtropical setting effectively reduces $CO_2$ emissions while providing additional co-benefits, notably water quality improvement.

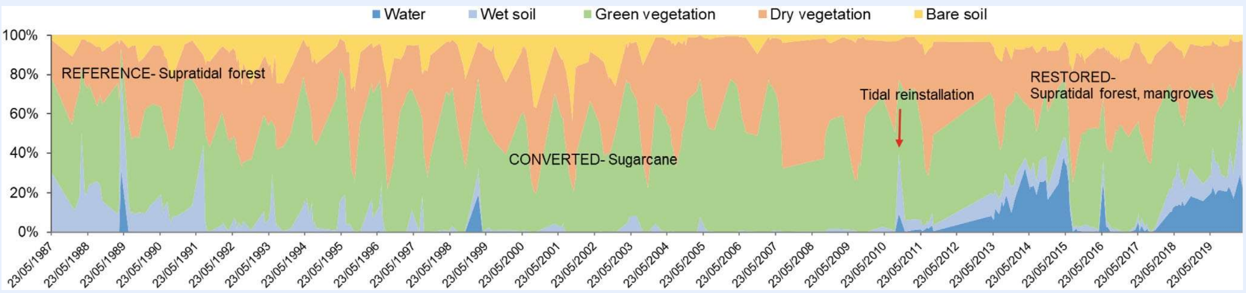



**Figure 10-2: Blue carbon case study**

## 10.4 Technology Readiness Potential and Commercial Readiness

| Technology Readiness | $/t CO2e | Key Evidence |
|---|---|---|
| 9 | 18-40 | McKinsey global blue carbon report estimates potential sequestration would be viable below US $18 (AUD $26) per tonne $CO_2$ (McKinsey 2022). However, based on |

| | | |
|---|---|---|
| | | results from Hagger et aal we estimate this is more likely to be above AUD$40.<br>For implementing the tidal restoration method hydrological restoration involves mainly earthworks for modification of drains/bunds, and costs can range AUD$ 8,591 $ha^{-1}$ for saltmarsh up to AUD$ 71,363 $ha^{-1}$ for mangroves. If there is a requirement to undertake hydrological this could cost AUD$ 20-40,000. Given natural recovery requires minimal maintenance, AUD$ 750 $ha^{-1}$ $yr^{-1}$ for the first five years of the project can be assumed (Waltham et al., 2021). Ongoing MRV costs might be required approximately every 5 years. |

| Commercial Readiness | Key Evidence |
|---|---|
| **3-4** | Some established restoration projects such as Blue Heart and Mungalla wetlands in Queensland and Hexham Swamp Hunter Valley have a higher level of commercial readiness and are seeking ERF accreditation and are applying for funding including through the Australian Government Blue Carbon Ecosystem restoration fund. Other green field sites have a low level of commercial readiness with up-front project development costs and complex approval processes constraining activity scaling. |

## 10.5 Scalability, Length of storage, Measurement and Verification

### Scalability

Projects in coastal wetlands face several challenges, including relatively high implementation costs complexity of legal rights in the coastal zone, and uncertainties related to species choice, ecological processes and climate change and extremes.

Several studies that have consulted with government, industry and private sector stakeholders have identified issues such as aggregation across landholdings and different types of tenure, cumbersome permitting, lack of appropriate policy frameworks, and lack of formal recognition of derived benefits as constraints to restoring coastal wetlands at-scale (e.g., Steven et al., 2021; Hagger et al., 2022b; Saunders et al., 2022).

Land tenure is a key constraint on the scalability of tidal restoration as much of the potential land is privately held (i.e., freehold) and suitable land is often in relatively small parcels (<100 ha), such that several farm-scale properties may need to be aggregated to achieve the scale of project required (Bell-James and Lovelock 2019; Bell-James et al., 2020; Shumway et al., 2021).

Technologically, the restoration methods available for reintroducing tides and planting mangroves are well-established and can increasingly be scaled with emerging technologies, such as the use of drones for seed dispersal. For seagrass, methods of planting or seeding are less mature though in some cases (e.g., SA, WA) modest successes of several hectares of cover through replanting are being achieved. Other methods using genetic, microbial and/or biogeochemical manipulation to increase carbon sequestration or reduce GHG emissions are also being developed.

## Length of storage

The principle of *permanence* requires that the net GHG reductions achieved in carbon sequestration projects must not be reversed. The term *durability* is also sometimes used for blue carbon projects because it allows the longevity of different carbon stocks, which can endure for centuries, or millennia to be compared.

The risk of reversal tends to be lower for blue carbon ecosystems because they are less susceptible to some of the risks that terrestrial ecosystems are prone to, such as fire. However, they are other risks associated with severe climate events such as marine heat waves which in 2010/11 resulted in the large-scale loss of seagrass in Shark Bay and in 2015/16 dieback of mangroves in Gulf of Carpentaria (Duke et al., 2017; Arias-Ortiz et al., 2018). Mitigation measures should be put in place to address risk of reversal and ensure durability over the longest timescale possible.

For the ERF blue carbon tidal method, project proponents can choose either a 25- or 100-year permanence period although it is anticipated that blue carbon projects would continue for 100 years, even if landholders initially enter into a 25-year agreement. A sequestration buffer is applied to sequestration estimated for tidal (re)introduction, instead of the permanence period discount and risk of reversal buffer that usually applied in other ERF sequestration methods.

## Measurement and Verification

Across all blue and teal carbon habitats more comprehensive measurements are required to better quantify rates of accumulation and long-term storage carbon, and the patterns of flux and net emissions of methane and nitrous oxide under different conditions (e.g., salinity, nutrient concentrations, geology, livestock, and feral animal disturbance). The data that has been collected to date has been mainly from individual research projects rather than systematic, government-initiated collection of this information.

Considering both the dearth of such information available for freshwater wetlands, and their large extent across Australia, prioritizing studies on the storage, sequestration, and fluxes and across Australia, are required to assess their sequestration potential.

More affordable methods for soil carbon measurement such as mid infra-red spectroscopy can be applied in coastal and marine environments, and the use of automated sensors for quantify fluxes and the development of earth observation proxies is also an active area of research. That will potentially assist in scaling and meeting measuring and verification needs.

More comprehensive and readily available mapping and change detection of blue and teal habitat extent and condition is required. Investments made recently under the national environmental accounting initiatives for saltmarsh and seagrass will provide greater certainty as to their potential for sequestration. However, greater ability to discriminate and attribute the cause of changes and to observe these at higher spatial and temporal resolution are required. The use of drones, coastal lidar and affordable access to high-resolution imagery is needed.

A key motivation for the development of modelling tools like BlueCAM is that they don’t require costly field measurements, ensuring consistency and reducing the costs borne by project proponents. However, for assessing the potential for inundation national hydrological models that can assess the extent and frequency of inundation of coastal and habitats and improved delineation of the areal extent over which management interventions may feasibly operate are also required.

## 10.6 Social, environmental impacts, risks and co-benefits

### Social impacts and risks

Coastal restoration, conducted either generally or specifically for the purpose of carbon sequestration , can lead to multiple social and economic benefits, including ongoing and even enhanced delivery of ecosystem services, social well-being, and support of livelihoods (Steven et al., 2021).

Where current agricultural use is of marginal value, carbon sequestration activities that result in the generation of ACCUs can be beneficial to landholders, particularly when coupled with other biodiversity and cultural benefits that blue carbon habitats provide.

First Nations people are the traditional owners and custodians of significant areas of blue carbon habitats. Free prior and informed consent (FPIC) involving meaningful and culturally appropriate consultations with stakeholders is considered best practice and must be the first step for any blue carbon project. Although Indigenous land tenure mapping is being developed, this information is often sensitive particularly where land tenure determination is still being resolved. A strategy for engagement and alignment with the values traditional owners hold for these habitats is required and there are long-term benefits from projects that are co-designed and led by traditional custodians, providing cultural benefits including ensuring the protection of cultural sites and maintaining Indigenous food systems and providing livelihood opportunities particularly for on-country maintenance and restoration of these habitats (Hagger et al., 2022b; Saunders et al., 2022).

### Environmental impacts and risks

Blue and teal carbon ecosystems are subject to a range of external stressors which may undermine the ongoing provision of ecosystem services and limit opportunities for GHG sequestration. The likelihood and consequence of such external stressors affecting blue and teal carbon ecosystems need to be considered in the design of sequestration projects and appropriate mitigations actions implemented.

Poor condition of coastal and teal wetlands in Australia can be the result of a legacy of poor management of soil and vegetation condition often resulting in accelerated soil erosion, acid sulphate soils while high densities of feral animals such as pigs, cattle, and buffalo continue to disturb soil and vegetation in blue and teal habitats particularly over large areas of northern Australia (Creighton et al., 2015; Waltham & Schaffer, 2021).

Depending on the setting, organic carbon pools and fluxes may be vulnerable to the impacts of short-term stressors such as cyclones and hurricanes or shifts in hydrology and marine heatwaves. In the medium term, rates of sea-level rise may enhance organic carbon burial in some parts of Australia, but in other regions, losses are anticipated to reduce sequestration (Young et al., 2021).

### Co-benefits

Blue carbon ecosystems provide multiple co-benefits, including biodiversity, fisheries enhancement, pollutant removal, coastal protection and can reduce pest incursions (Barbier et al., 2011). They are culturally important to Indigenous people who rely on them for a variety of materials and resources (Clarke et al., 2021).

Trade-offs among carbon sequestration and these co-benefits are generally negligible, and hotspots can be identified where multiple benefits can be bundled to attain higher carbon prices for restoration projects, or to undertake projects under emerging markets, such as for biodiversity. As these ecosystem services vary regionally and locally, relevant, systematic data collection and the development of modelling tools are required.

Prioritising sites by cost-effectiveness and co-benefits can achieve multiple ecosystem services and higher carbon prices might be achieved by bundling (combining) or stacking (selling benefits separately) different ecosystem services. There is a substantial appetite for these kinds of units and the development of methods for quantification and valuation of these co-benefits – as well as for natural capital accounting – is a priority in Australia.

## 10.7 Barriers to implementation:

Figure 10-4 conceptualises many of issues to be considered in developing blue carbon projects and some of these are briefly discussed further below (Stewart-Sinclair et al., 2021).

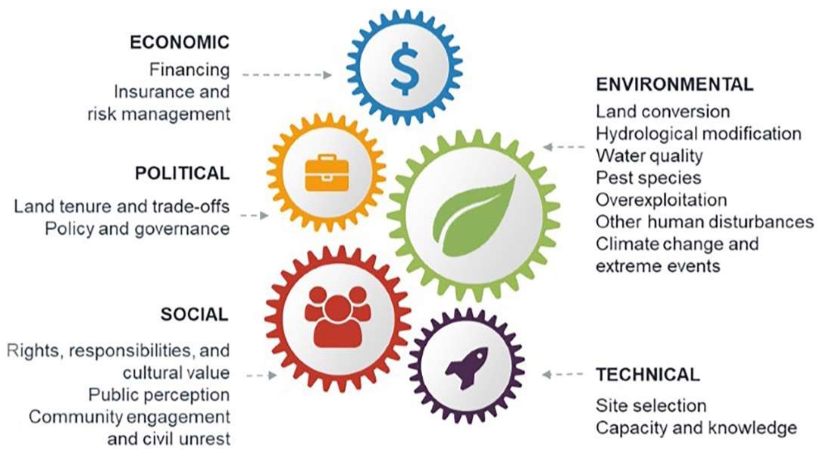



**Figure 110-4 Blue carbon benefits and risks**

### 10.1.1 Policy and regulatory environment

Australian legislation and policies do not uniformly integrate nor recognise all ecosystem services provided by blue and teal ecosystems. Under the Australian constitution, states and territories hold the legislative power to regulate coastal environmental policy and planning, which in turn shapes the management options available for implementing carbon sequestration programs.

Issues of land tenure and rights to carbon sequestration are also complex in the coastal zone and vary among jurisdictions: who has the right to the land on which the project is located and for how long, and in turn, who has the right to carbon credits flowing from the project. On leasehold land, the lease term and purpose are required to meet the duration of the blue carbon project. On freehold land, landowners may need to be granted use of land below the tidal boundary, which is generally owned by the state (Bell-James & Lovelock, 2019). Activities including (re)introduction of tidal flow and land-use planning for sea-level rise may initiate shifts in tidal boundaries, which further complicate rights to carbon (Bell-James and Lovelock, 2021).

Multi-agency approval processes can be time- and cost-prohibitive and are considered nationally to be a major barrier to projects across Australia (Saunders et al., 2022). Such approvals usually fall into two categories: development permits intended for infrastructure projects, and research permits usually for short, pilot projects. Altering leases and negotiating carbon rights and seeking regulatory approvals for the installation or removal of structures adds additional administrative burden and costs. In Queensland for example, fish barrier remediation, which is similar to tidal restoration, incurred $45,000 in approval fees and required expertise to complete the approval documentation (Hagger et al. 2022b).

For certain blue carbon projects demonstrating *additionality* presents unique challenges, particularly because of the overlap between blue carbon ecosystems and declared marine protected areas, national conservation priorities, and sustainable coastal wetland management where protections may focus on fisheries management rather than maintaining blue carbon ecosystems.

Thus, regional variation in policy pertaining to coastal restoration will be an important factor to consider when assessing the feasibility of sites for blue carbon projects. The permit and approval process from state governments could be streamlined for tidal restoration projects, and clearer articulation of steps to gain approvals would help reduce the barrier to project implementation (Saunders et al., 2022). Clear policies to support tidal restoration of coastal wetlands, could increase the attractiveness of coastal wetland restoration, particularly if administrative processes were simpler and easier to negotiate.

### 10.1.2 Technology performance variability

The performance of blue and teal carbon projects around Australia may vary depending on regional ecosystem type, condition and performance, and the prevailing policy setting. At a project level, proponents' technical understanding of basic ecological and physiological requirements (e.g., low tide exposure) and their adoption of emerging technologies will affect the project's success. Costs of entry, long (decadal) timeframes for a return on investment, and ongoing monitoring reporting and verification (MRV) requirements are further factors that will influence the success or otherwise of projects.

Data deficiencies for predicting the feasibility of blue carbon projects, including the resolution of tidal planes, accurate income data from different land-uses, accurate costing of restoration, and mapping of hydrological modifications. Increasing the range of case study regions would further help understand the extent of tidal restoration opportunities and limitations across Australia.

Models such as the Australian Land Use Trade-Off model (LUTO) used to assess carbon sequestration in terrestrial vegetation and soils could also be used to examine feasible sequestration in mangroves and saltmarsh by incorporating changes in land-use and drainage as well as economic and tenure considerations.

### 10.1.3 Financial proposition and costs and access to capital

The studies of Hagger et al., (2022a, b) summarised in section 11.2 provide regional insight into the factors determining the profitability of blue carbon projects and demonstrate that carbon prices in Australia are too low for many projects to achieve profitability (although the current spot price for ACCUs is higher than the threshold for profitability in some of their scenarios) and that bundling or stacking of other co-benefits is the most viable medium-term solution (Hagger et al., 2022a, b).

Up-front project establishment costs can be high and include regulatory approvals, hydrological modelling, capital outlays to remove or emplace structures and to conduct earths works. Maintenance and meeting ongoing MRV requirements must also be factored into assessments of the financial viability of any proposed projects. Studies from forest carbon projects have shown that costs of monitoring and verification can exceed the revenue from carbon credits and that cost is a critical component in the development of forest carbon methods that provide incentives (Köhl et al., 2020). A key motivation for the development of modelling tools like BlueCAM is that don't require costly field measurements of sequestration and so reduce the costs borne by project proponents.

For projects in Australia that involve a direct restoration of habitat, the high cost of labour and logistics generally makes restoration-based activities comparatively more costly than in many other countries, though they are generally comparable to the USA and Europe. The best available cost estimates from a global review of restoration (Bayraktarov et al., 2015) found that for developed nations, the median cost per hectare of mangroves, saltmarsh, and seagrass restoration in 2010 AUD dollars (1 USD = 1.46 AUD) were: mangroves, $ 71,000; saltmarsh, $293,000; and for seagrass $575,000. However, many of the estimates used were from research studies, which are not likely to reflect reliably the costs incurred by restoration practitioners. In the case of seagrass restoration (transplanting or use of seeding methods), engaging professional labour results in a total restoration cost that is 2.7 to 3.6 more costly than using volunteer labour Irrespective of the labour used – the operational costs of boat and car hire, accommodation if the site is remote, and material costs for transplantation can be around AUD $7,000 per ha (Rogers et al. 2021).

As data on the costs of implementing blue carbon projects become available over coming years, a more accurate assessment of the costs and benefits will emerge. Certainly, the most cost-effective investments at present are larger-scale, volunteer-based restoration projects.

### 10.1.4 Industry supply chains and skills

The translation of blue carbon science into policy and practice will increasingly require transdisciplinary collaborations to overcome uncertainties in social, governance, financial and technological dimensions (Macreadie et al. 2022). In many parts of Australia, and increasingly nationally, they are networking and collaborating amongst themselves and with regulatory and funding agencies to implement such projects at scale (Saunders et al., 2022).

### 10.1.5 Market opportunities or market creation

The potential to mobilize climate and adaptation finance to support scaling of blue carbon projects is growing internationally. Coalitions of actors are collaborating to establish financial guidance, novel fit-for purpose investment products sand funds that can be accessed by project proponents and investors in blue carbon projects (Vanderklift et al., 2019, 2022; WEF 2022).

There is considerable interest from the private sector in investing in blue carbon projects, the motivations for which range from meeting Corporate Stewardship Responsibilities (CSR), seeking recognition of their investments as environmental offsets for their business activities, or revenue streams from verified crediting of various ecosystem services (e.g., carbon, biodiversity).

The multiple benefits that blue carbon projects offers is drawing significant interest among investors, sellers, and buyers who seek to build resilience, reduce biodiversity loss, and capture and sequester carbon (WEF 2022). Their development will require consideration of issues such as additionality, permanence, fungibility, and methods to verify and validate outcomes — all aspects that buyers are likely to demand. Stacking is likely not a viable option for most benefits in the near term because the market infrastructure to validate, verify and trade them is not yet developed.

## 10.8 Scaling knowledge gaps

Scaling knowledge gaps that need to be addressed include:

- *Where are the potential and feasible areas for blue and teal carbon projects?* Improved mapping and change detection of the areal extent of blue and teal ecosystems is required for assessment of overall carbon sequestration potential at the national scale. National-scale hydrological models are needed for better estimation of potential areas of inundation and need to be informed by data and mapping of infrastructure, including tidal barrier structures that may impede ingress. Furthermore, mapping the condition of coastal wetlands would enable exploration of restoration activities to enhance condition, which would increase carbon sequestration and co-benefits.
- *What are the life cycle costs for Blue and teal carbon projects?* Regional data on restoration costs including approval, capital, and maintenance costs for restoration activities would also improve assessments of economic feasibility.
- *What is the carbon sequestration potential of other lesser understood Blue and Teal Ecosystems*? For subtidal seagrass better mapping, monitoring and research are required to understand fluxes and rates of carbon accumulation and long-term sequestration pathways. Given the areal extent of damaged freshwater wetlands, there could be considerable potential in restoration of teal carbon as a potential sequestration method. Prioritizing studies on the carbon storage, sequestration and GHG fluxes with these habitats and across Australia, are required to assess their potential.
- *What are the sequestration and emission rates of GHG and permanence of storage*? More information is needed on the patterns of flux and net emissions of methane and nitrous oxide under different circumstances (e.g., salinity, nutrient concentrations, geology, livestock and feral animal disturbance), and the temporal patterns of change in net emissions with restoration. Long-term measurement programs within situ instrument deployments are required. Emissions might be considerable in some teal carbon ecosystems, in which low salinity and nutrient enrichment may enhance methane and nitrous oxide emissions. Emission factors for activities like kelp restoration and seabed trawling are yet to be developed.
- *What are requirements and opportunities for Indigenous engagement?* Identification of cultural heritage values would allow explicit inclusion of cultural heritage in the co-benefits of blue and teal ecosystems. Development of an Indigenous blue carbon strategy that is action-orientated and regionally specific to ensure collaboration with Traditional Custodians in planning of blue carbon restoration programs.

## 10.9 Chapter References


Australian Bureau of Statistics, (2022). National Ocean Account, Experimental Estimates: Experimental estimates to measure changes in ocean ecosystems from 1987 to 2021. Retrieved 12th September 2022, 2022, from: https://www.abs.gov.au/statistics/environment/environmental-management/national-ocean-account-experimental-estimates/aug-2022:.

Arias-Ortiz, A., O. Serrano, P. Masqué, P. S. Lavery, U. Mueller, G. A. Kendrick, M. Rozaimi, A. Esteban, J. W. Fourqurean, N. Marbà, M. A. Mateo, K. Murray, M. J. Rule and C. M. Duarte (2018). A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. Nature Climate Change 8 (4): 338-344.

Arias-Ortiz, A., P. Y. Oikawa, J. Carlin, P. Masqué, J. Shahan, S. Kanneg, A. Paytan and D. D. Baldocchi (2021). Tidal and Nontidal Marsh Restoration: A Trade-Off Between Carbon Sequestration, Methane Emissions, and Soil Accretion. Journal of Geophysical Research: Biogeosciences 126 (12).

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier and B. R. Silliman (2011). The value of estuarine and coastal ecosystem services. Ecological monographs 81 (2): 169-193.

Bayraktarov, E., S. Brisbane, V. Hagger, C. S. Smith, K. A. Wilson, C. E. Lovelock, C. Gillies, A. D. L. Steven and M. I. Saunders (2020). Priorities and Motivations of Marine Coastal Restoration Research. Frontiers in Marine Science 7.

Bell-James, J. (2016). Developing a framework for 'blue carbon' in Australia: legal and policy considerations.

Bell-James, J., T. Boardman and R. Foster (2020). Can't see the (mangrove) forest for the trees: Trends in the legal and policy recognition of mangrove and coastal wetland ecosystem services in Australia. Ecosystem Services 45.

Bell-James, J. and C. E. Lovelock (2019). Legal barriers and enablers for reintroducing tides: An Australian case study in reconverting ponded pasture for climate change mitigation. Land Use Policy 88.

Bino, G., R. T. Kingsford and K. Brandis (2016). Australia's wetlands – learning from the past to manage for the future. Pacific Conservation Biology 22 (2).

Carnell, P. E., M. M. Palacios, P. Waryszak, S. M. Trevathan-Tackett, P. Masque and P. I. Macreadie (2022). Blue carbon drawdown by restored mangrove forests improves with age. J Environ Manage 306: 114301.

Carnell, P. E., S. M. Windecker, M. Brenker, J. Baldock, P. Masque, K. Brunt and P. I. Macreadie (2018). Carbon stocks, sequestration, and emissions of wetlands in southeastern Australia. Glob Chang Biol 24 (9): 4173-4184.

Clarke, B., A. K. Thet, H. Sandhu and S. Dittmann (2021). Integrating Cultural Ecosystem Services valuation into coastal wetlands restoration: A case study from South Australia. Environmental Science & Policy 116: 220-229.

Commonwealth of Australia (2021). National Inventory Report 2019: *The Australian Government Submission to the United Nations Framework Convention on Climate Change*

Costa, M., C. E. Lovelock, N. J. Waltham, M. M. Moritsch, D. Butler, T. Power, E. Thomas and P. I. Macreadie (2021). Modelling blue carbon farming opportunities at different spatial scales. J Environ Manage 301: 113813.

Costa, M., C. E. Lovelock, N. J. Waltham, M. Young, M. F. Adame, C. V. Bryant, D. Butler, D. Green, M. A. Rasheed, C. Salinas, O. Serrano, P. H. York, A. A. Whitt and P. I. Macreadie (2021). Current and future carbon stocks in coastal wetlands within the Great Barrier Reef catchments. Glob Chang Biol 27 (14): 3257-3271.

Creighton, C., Boon, P. I., Brookes, J. D., & Sheaves, M. (2015). Repairing Australia's estuaries for improved fisheries production – what benefits, at what cost? *Marine and Freshwater Research, 66*(6), 493-507.

Costa, M. and P. I. Macreadie (2022). The Evolution of Blue Carbon Science. Wetlands 42 (8).

Duke, N. C., J. M. Kovacs, A. D. Griffiths, L. Preece, D. J. E. Hill, P. van Oosterzee, J. Mackenzie, H. S. Morning and D. Burrows (2017). Large-scale dieback of mangroves in Australia. Marine and Freshwater Research 68 (10).

Filbee-Dexter, K. and T. Wernberg (2020). Substantial blue carbon in overlooked Australian kelp forests. Scientific Reports 10 (1).

Hagger, V., N. J. Waltham and C. E. Lovelock (2022a). Opportunities for coastal wetland restoration for blue carbon with co-benefits for biodiversity, coastal fisheries, and water quality. Ecosystem Services 55.

Hagger, V., Stewart-Sinclair, P. Rossini, R. Waltham, N.J., Ronan, M., Adame, M.F., Lavery, P., Glamore, W. and Lovelock, C.E. (2022b). Coastal wetland restoration for blue carbon in Australia. Values-based approach for selecting restoration sites. Report to the National Environmental Science Program. The University of Queensland.

Hill, R., A. Bellgrove, P. I. Macreadie, K. Petrou, J. Beardall, A. Steven and P. J. Ralph (2015). Can macroalgae contribute to blue carbon? An Australian perspective. Limnology and Oceanography: n/a-n/a.

Iram, N., D. T. Maher, C. E. Lovelock, T. Baker, C. Cadier and M. F. Adame (2022). Climate change mitigation and improvement of water quality from the restoration of a subtropical coastal wetland. Ecol Appl: e2620.

Kelleway, J., Serrano, O., Baldock, J., Cannard, T., Lavery, P., Lovelock, C., Macreadie, P., Masqué, P., Saintilan, N., Steven, A., 2017. Technical Review of Opportunities for Including Blue Carbon in the Australian Government's Emissions Reduction Fund. Department of the Environment and Energy, Canberra, pp. 287.

Kelleway, J. J., O. Serrano, J. A. Baldock, R. Burgess, T. Cannard, P. S. Lavery, C. E. Lovelock, P. I. Macreadie, P. Masqué, M. Newnham, N. Saintilan and A. D. L. Steven (2020). A national approach to greenhouse gas abatement through blue carbon management. Global Environmental Change 63.

Köhl, Michael, Prem Raj Neupane, and Philip Mundhenk. 2020. REDD+ measurement, reporting and verification – A cost trap? Implications for financing REDD+MRV costs by result-based payments, *Ecological Economics*, 168.

Lymburner, L., P. Bunting, R. Lucas, P. Scarth, I. Alam, C. Phillips, C. Ticehurst and A. Held (2020). Mapping the multi-decadal mangrove dynamics of the Australian coastline. Remote Sensing of Environment 238.

Lovelock, C. E., M. F. Adame, J. Bradley, S. Dittmann, V. Hagger, S. M. Hickey, L. B. Hutley, A. Jones, J. J. Kelleway, P. S. Lavery, P. I. Macreadie, D. T. Maher, S. McGinley, A. McGlashan, S. Perry, L. Mosley, K. Rogers and J. Z. Sippo (2022). An Australian blue carbon method to estimate climate change mitigation benefits of coastal wetland restoration. Restoration Ecology.

Lovelock, C. E., T. Atwood, J. Baldock, C. M. Duarte, S. Hickey, P. S. Lavery, P. Masque, P. I. Macreadie, A. M. Ricart, O. Serrano and A. Steven (2017). Assessing the risk of carbon dioxide emissions from blue carbon ecosystems. Frontiers in Ecology and the Environment 15 (5): 257-265.

Lovelock, C. E. and B. M. Brown (2019). Land tenure considerations are key to successful mangrove restoration. Nat Ecol Evol 3 (8): 1135.

Lovelock, C. E., J. Sippo, M. F. Adame, S. Dittmann, S. Hickey, L. Hutley, A. Jones, J. Kelleway, P. Lavery, P. Macreadie, D. Maher, L. Mosely and K. Rogers (2021). Blue Carbon Accounting Model (BlueCAM) Technical Overview. Prepared for the Clean Energy Regulator. Canberra Australia.

McKinsey and Company (2020). Blue carbon: The potential of coastal and oceanic climate action.

Macreadie, P. I., Q. R. Ollivier, J. J. Kelleway, O. Serrano, P. E. Carnell, C. J. Ewers Lewis, T. B. Atwood, J. Sanderman, J. Baldock, R. M. Connolly, C. M. Duarte, P. S. Lavery, A. Steven and C. E. Lovelock (2017). Carbon sequestration by Australian tidal marshes. Sci Rep 7: 44071.

Macreadie, P. I., A. I. Robertson, B. Spinks, M. P. Adams, J. M. Atchison, J. Bell-James, B. A. Bryan, L. Chu, K. Filbee-Dexter, L. Drake, C. M. Duarte, D. A. Friess, F. Gonzalez, R. Q. Grafton, K. J. Helmstedt, M. Kaebernick, J. Kelleway, G. A. Kendrick, H. Kennedy, C. E. Lovelock, J. P. Megonigal, D. T. Maher, E. Pidgeon, A. A. Rogers, R. Sturgiss, S. M. Trevathan-Tackett, M. Wartman, K. A. Wilson and K. Rogers (2022). Operationalizing marketable blue carbon. One Earth 5 (5): 485-492.

Mazarrasa, I., P. Lavery, C. M. Duarte, A. Lafratta, C. E. Lovelock, P. I. Macreadie, J. Samper-Villarreal, C. Salinas, C. J. Sanders, S. Trevathan-Tackett, M. Young, A. Steven and O. Serrano (2021). Factors Determining Seagrass Blue Carbon Across Bioregions and Geomorphologies. Global Biogeochemical Cycles 35 (6).

Moritsch, M. M., M. Young, P. Carnell, P. I. Macreadie, C. Lovelock, E. Nicholson, P. T. Raimondi, L. M. Wedding and D. Ierodiaconou (2021). Estimating blue carbon sequestration under coastal management scenarios. Sci Total Environ 777: 145962.

Needelman, Brian A., Igino M. Emmer, Stephen Emmett-Mattox, Stephen Crooks, J. Patrick Megonigal, Doug Myers, Matthew P. J. Oreska, and Karen McGlathery. 2018. The Science and Policy of the Verified Carbon Standard Methodology for Tidal Wetland and Seagrass Restoration, *Estuaries and Coasts*, 41: 2159-71.

Negandhi, K., G. Edwards, J. J. Kelleway, D. Howard, D. Safari and N. Saintilan (2019). Blue carbon potential of coastal wetland restoration varies with inundation and rainfall. Sci Rep 9 (1): 4368.

Rogers, A. A., C. Gillies, B. Hancock, I. McLeod, A. Nedosyko, S. Reeves, L. Soloranzo and M. P. Burton (2018). Benefit-cost analysis for marine habitat restoration: a framework for estimating the viability of shellfish reef repair projects. Report to the National Environmental Science Programme, Marine Biodiversity Hub, (Perth: The University of Western Australia).

Rogers, K., K. K. Lal, E. F. Asbridge and P. G. Dwyer (2022). Coastal wetland rehabilitation first-pass prioritisation for blue carbon and associated co-benefits. Marine and Freshwater Research.

Rogers, K., Boon, P. I., Branigan, S., Duke, N. C., Field, C. D., Fitzsimons, J. A., Kirkman, H., Mackenzie, J. R., & Saintilan, N. (2016, 2016/10/01/). The state of legislation and policy protecting Australia's mangrove and salt marsh and their ecosystem services. *Marine Policy, 72*, 139-155

Saunders, M. I., N. J. Waltham, T. Cannard, M. Sheppard, M. Fischer, Alice Twomey, M. Bishop, K. Boody, D. Callaghan, B. Fulton, Catherine E. Lovelock, Mariana Mayer Pinto, Ian M. McLeod, T. McPherson, R. Morris, A. Pomeroy, M. Ronan, S. Swearer and A. Steven (2022). A roadmap for coordinated landscape- scale coastal and marine ecosystem restoration. A Report to the National Environmental Science Program. Brisbane QLD, CSIRO.

Serrano, O., C. E. Lovelock, T. B. Atwood, P. I. Macreadie, R. Canto, S. Phinn, A. Arias-Ortiz, L. Bai, J. Baldock, C. Bedulli, P. Carnell, R. M. Connolly, P. Donaldson, A. Esteban, C. J. Ewers Lewis, B. D. Eyre, M. A. Hayes, P. Horwitz, L. B. Hutley, C. R. J. Kavazos, J. J. Kelleway, G. A. Kendrick, K. Kilminster, A. Lafratta, S. Lee, P. S. Lavery, D. T. Maher, N. Marbà, P. Masque, M. A. Mateo, R. Mount, P. J. Ralph, C. Roelfsema, M. Rozaimi, R. Ruhon, C. Salinas, J. Samper-Villarreal, J. Sanderman, C. J. Sanders, I. Santos, C. Sharples, A. D. L. Steven, T. Cannard, S. M. Trevathan-Tackett and C. M. Duarte (2019). Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. Nature Communications 10 (1).

Steven, A. D. L., C. Cameron, T. Cannard, V. Hagger, E. Kenna, C. Lovelock, M. Saunders, G. Scheufele and M. Vanderklift (2022). Design, Prioritisation and Assessment Principles for Blue Carbon Ecosystem Restoration and Accounting Report. Final Report to Department of Agriculture, Water and the Environment. Australia, CSIRO**:** 60.

Stewart-Sinclair, P. J., J. Purandare, E. Bayraktarov, N. Waltham, S. Reeves, J. Statton, E. A. Sinclair, B. M. Brown, Z. I. Shribman and C. E. Lovelock (2020). Blue Restoration – Building Confidence and Overcoming Barriers. Frontiers in Marine Science 7.

Vanderklift, M., Steven, A., Benzaken, D., Thiele (2022). Blue forest finance: financing the protection and restoration of blue forests and meadows. Australia., CSIRO.

Vanderklift, M. A., R. Marcos-Martinez, J. R. A. Butler, M. Coleman, A. Lawrence, H. Prislan, A. D. L. Steven and S. Thomas (2019). Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. Marine Policy.

Waltham, N. J., & Schaffer, J. (2021). Will fencing floodplain and riverine wetlands from feral pig damage conserve fish community values? *Ecology and Evolution, 11*(20), 13780- 13792

World Economic Forum (2022). High-Quality Blue Carbon Principles and Guidance: A Triple-Benefit Investment for People, Nature, and Climate.

Whitt, A. A., C.E. Lovelock, M. Young, R. Coleman, C. L. Gillies, J. Bell-James, and P.I. Macreadie. (subm.). The importance of land tenure in planning coastal wetland adaption to sea-level rise.

Williamson, P. and J.-P. Gattuso (2022). Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, With Questionable Climatic Cost-Effectiveness. Frontiers in Climate 4.

Young, M. A., O. Serrano, P. Macreadie, C. E. Lovelock, P. Carnell and D. Ierodiaconou (2021). National scale predictions of contemporary and future blue carbon storage. Science of The Total Environment

# 11 Pyrolysis Biochar Systems

| | | |
|---|---|---|
| **Emission Type** | Abated | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Table 11-1: Pyrolysis biochar technology type**

## 11.1 Summary

**Description and current uptake**

Pyrolytic carbon capture and storage (PyCCS) describes the process of using biomass growth (photosynthesis) to capture atmospheric carbon dioxide ($CO_2$) and pyrolysis technologies (thermal decomposition) to lock a portion of that carbon into biochar.

Biochar is a charcoal-like material produced during the thermal breakdown of organic biomass under oxygen limited conditions. Feedstocks for the process include forestry and crop residues, and food, green or municipal organic waste. It is valued for its stable porous structure, high surface area, sorption characteristics (reversible adherence) for metals and ability to accelerate (catalyse) biochemical reactions.

Under Australia's Emissions Reduction Fund (ERF), the application of biochar to agricultural soil is an eligible activity. However, application to soils remains low due to high costs of biochar (>$500 per t), uncertainty in agronomic benefit (Section 11.6.3), availability and logistical challenges in transport and application.

**Sequestration potential**

Biochar has high sequestration potential and global sequestration potential is estimated at 0.7–1.3 Gt $CO_2$ per year. The theoretical sequestration potential for biochar and bioenergy in Australia is estimated to be 30–60 Mt carbon dioxide equivalents ($CO_2$-e) per year. This wide range reflects uncertainties in annual biomass availability under climate variability and competing uses of biomass resources. Estimating economic sequestration is challenging and faces additional constraints related to logistics and economics.

**Technology readiness potential and commercial readiness**

The technology readiness of pyrolysis technologies for producing biochar is generally proven and ready for full commercial deployment. There are several commercial biochar producers across Australia, but information on their scale of production, commercial propositions and associated technical and financial performance is difficult to obtain.

In Queensland, Logan Water has established a $28 M biosolids gasification facility to drive the Councils carbon neutral ambitions. The project is expected to reduce carbon emissions by 6000 tonnes per year, save $1 M in waste management operational costs, and create new revenue streams from biochar sales. The produced biochar is likely to be used in land applications to support crop productivity and carbon sequestration and provides an exemplar of waste-to-energy solutions with multiple benefits.

The international biochar market is projected to be US$3.1 billion by 2025. Several companies are aiming to leverage capital investment and international interest to produce biochar at the industrial scale in Australia.

**Scalability, length of storage, measurement and verification**

The global biochar industry tends to have many relatively small producers, although larger-scale operations are emerging. Centralised pyrolysis biochar facilities and networks of smaller-scale units have been proposed as ways to address scalability issues. Co-locating pyrolysis facilities with other biomass and/or waste management facilities can also help scale biochar production.

Carbon as biochar can remain stable in the environment for many years: mean residence times typically range between 300 and 600 years and can be over 1,000 years. By contrast, raw biomass generally decomposes in less than 10 years. The ratio of hydrogen to organic carbon is used for measuring the carbon sequestered in biochar. This test is available through commercial analytical laboratories.

**Social, environmental impacts, risks and co-benefits**

Social considerations for biochar relate to issues of food security (possible tension between land used for food production or biomass generation), community acceptance (environmental impacts, acceptability of centralised location of biomass or waste facilities) and possible risk to human health (possible irritant to lungs and eyes, may contain harmful components).

Potential environmental hazards arise from biochar's structure and particle size, possible harmful components (such as heavy metals, dioxins, polycyclic aromatic hydrocarbons) and possible biochemical interactions. There are existing standards, credentialling systems, and risk frameworks suitable in managing many of these risks. It would be valuable to strengthen methods and guiding frameworks to protect vulnerable environments and ensure a social license to operate.

Many co-benefits can be derived from biochar, depending on the type of biochar produced and its end-use. Biochar can be used as a soil amendment to improve soil condition and as a supplement in animal feed to moderate the impact of high nutrient loads. It can be added to composting systems and used in landscape management and remediation. Biochar embedded in carbon-based composite materials can enhance mechanical properties and durability.

**Barriers to implementation**

Australia's ERF currently does not provide a mechanism to credit the stable carbon within biochar itself. There is a need for broader policy incentives to drive industry investment and development beyond soil application alone. Accounting for carbon capture and storage (CCS) potential at the point of production, considering end-use, could provide a cost-effective approach towards incentives.

Pyrolysis biochar systems are gaining acceptance to gain value from biomass, capture carbon and support a range of place-specific co-benefits. Social licence and acceptance of biochar is intrinsically linked to that of bioenergy. In bioenergy cropping, trust has been identified as the key variable in gaining social licence to operate.

The pricing of biochar has been variable over the past decade and end-use markets for biochar are still not well established. However, with very low production rates, current demand for biochar in Australia outstrips supply and there are significant opportunities for creating new, low carbon industries and jobs around pyrolysis biochar systems.

**Scaling knowledge gaps**

There has been considerable fundamental research into how different types of biochar behave in the environment and how it can be used to support agricultural productivity, land remediation or industrial applications. However, techno-economic and social research within a whole of systems context is under-represented. As the value proposition of pyrolysis biochar systems is place dependent, this should play an important role in focusing Australian research efforts for informing economic sequestration potential, quantifying relevant co-benefits and garnering social licence.

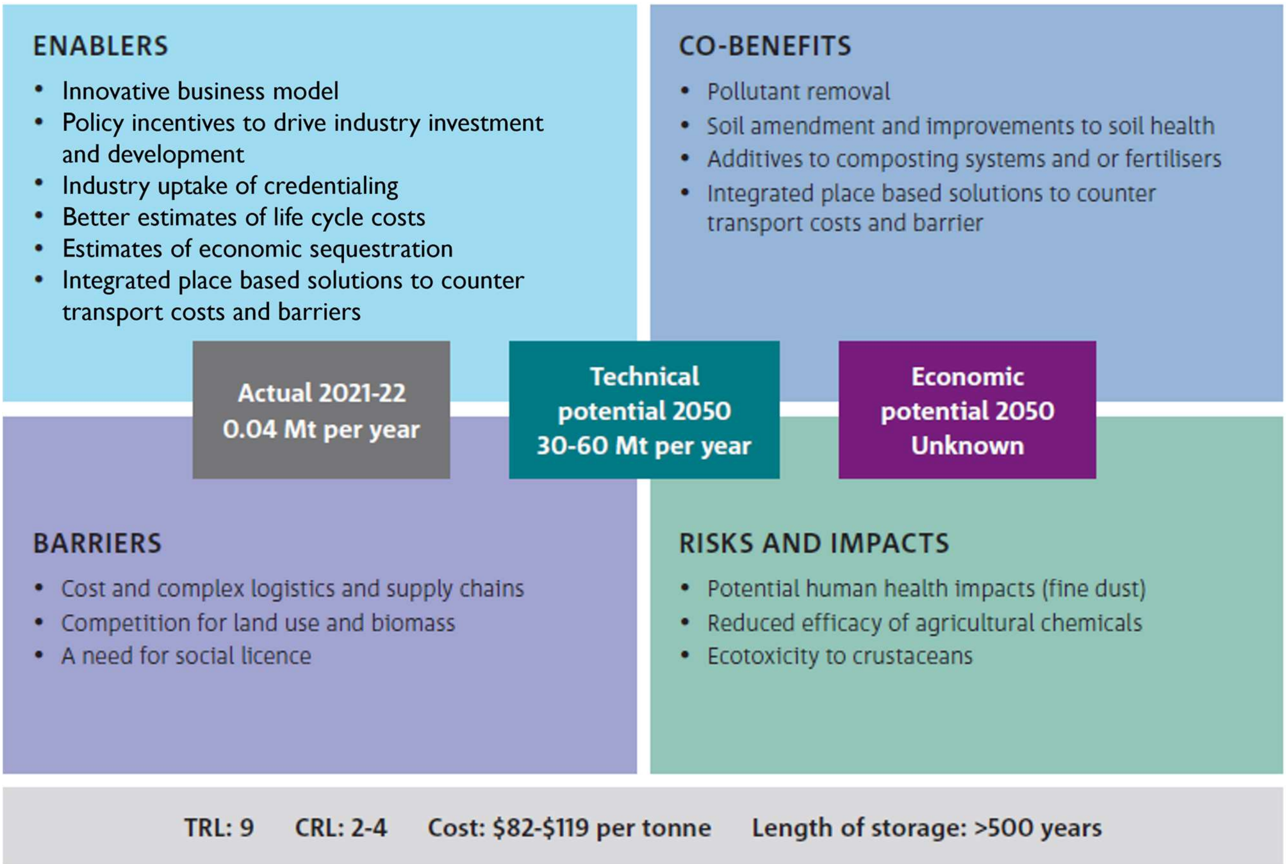



**Figure 11-1: Summary of pyrolysis biochar.**

## 11.2 Description and current uptake

Biochar is a stable, carbon-rich, charcoal-like material that is produced during the thermal decomposition of organic biomass under oxygen limited conditions. The organic biomass used as feedstocks include forestry and crop biomass, and food-, green-, or municipal- wastes.

Biomass is converted to energy (gas), liquids (bio-oils, water soluble components), and biochar through thermal technologies such as pyrolysis, hydrothermal carbonisation, gasification, or torrefaction (Table 11-1). The yield, stability, and appropriate end-use of biochar is dependent on the biomass used, production technology and operating conditions (temperature, residence time). In the context of carbon offset technology, pyrolytic carbon capture and storage (PyCCS) describes the process of using biomass growth (photosynthesis) to capture atmospheric $CO_2$ and pyrolysis technologies to lock a portion of that carbon into a stable biochar (Schmidt et al 2019). PyCCS aims to optimise the process to favour the production of long-term stable carbon as biochar and highly aromatic bio-oils. As a guideline, slow pyrolysis between 450°C and 700°C is considered optimal for PyCCS, with biochar conversion efficiencies (30-50%). In comparison, fast pyrolysis (>700°C) has low biochar yields, high energy expenditure, and is less suited to carbon sequestration.

| THERMOCHEMICAL TECHNOLOGY | | TEMPERATURE | PRODUCTS |
|---|---|---|---|
| **Slow Pyrolysis** | Slow-rate heating of biomass in the absence of oxygen and requiring residence periods of > 5 minutes. | 450 – 700 °C (~10°C/min) | Biochar, with smaller portions of liquid, gases. |
| **Fast Pyrolysis** | High-rate heating of biomass in the absence of oxygen, requiring relatively dry | 600 – 1000 °C | Liquids, gases, smaller portions of biochar. |

| | | | |
|---|---|---|---|
| | biomass (<10% moisture), and residence times in the range of seconds. | | |
| **Hydrothermal carbonisation** | Heating biomass in water under high pressure for several hours. | 180 – 250 °C | Hydro-char, gases. |
| **Gasification** | Heating in the presence of steam and high pressure to achieve partial oxidation of biomass | 700 – 1200 °C | Liquid, gases, smaller portions of biochar. |
| **Torrefaction** | incomplete pyrolysis of biomass at atmospheric pressure | 200 – 300 °C | Gases, Liquids, smaller portions of biochar. |

**Table 11-1: Description of thermochemical technologies used to convert biomass to non-condensable gases (e.g. $CO_2$, CO, $CH_4$) , liquids (bio-oils and water soluble components) and biochar (solid) products.**

To ensure the permanence of PyCCS offsets, the end-use application of biochar must maintain its permanence. Figure 11-3 depicts a simple linear pyrolysis biochar value chain with end-use application in soil. Used as a soil amendment, biochar-carbon remains stable and can bring agronomic co-benefits such as improved soil condition and plant growth (see 11.6.3). Early research evaluating the use of biochar in soils was dominated by single, surface broadcast applications of 5 – 50 tonnes per hectare ($t.ha^{-1}$) incorporated through ploughing (Schmidt et al 2021). These studies support an understanding of the potential co-benefits on soil condition (e.g. soil structure, nutrient cycling), but often raise criticism from a practical and economic perspective. Current advise for surface broadcast and incorporation is typically 5 t per ha, which is comparable to typical rates of chicken litter application. However, there are examples of lower rate application (~200 kg/ha), in-furrow banding (Blackwell et al 2010), and industry development towards biochar granules that are suited to air-seeder application. An industry drive towards biochar enhanced granular fertilisers (mineral or organic) has potential to increase the practical feasibility of soil application with annual application of low doses as slow-release fertilisers (Wang et al 2022).

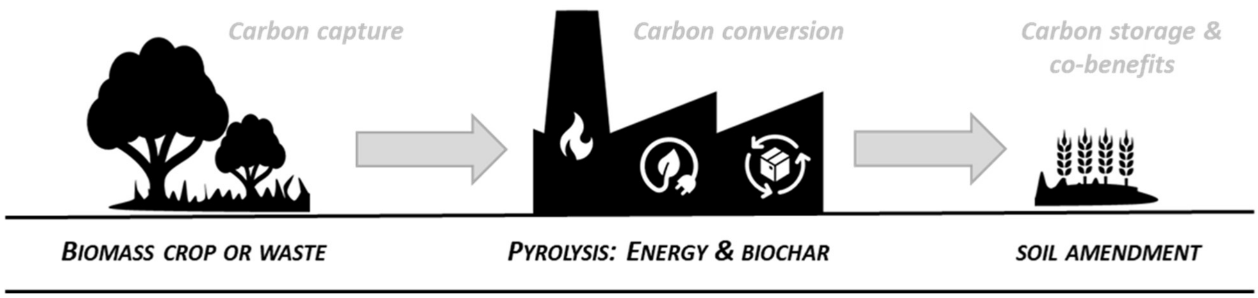



**Figure 11-2: Schematic depicting a simple linear pyrolysis biochar value chain where: a) plants capture $CO_2$ in biomass; b) pyrolysis technologies convert biomass to energy and stable carbon (biochar); c) carbon is stored in the environment where it is very slow to break down (>500 years) but brings co-benefits through soil improvement or remediation.**

The value of biochar as a soil amendment is based on the stable porous structure, high surface area, sorption characteristics (reversible adherence) and ability to accelerate (catalyse) biochemical reactions. These behaviours make biochar useful in a broad range of environmental and industrial applications including in combination with composts or fertilisers, in animal feeds, as a sorbent for remediation, and in composite materials or industrial applications (11.5.3).

Variation in properties and behaviours of biochar produced from different biomasses and under different conditions poses both challenges and opportunities for the industry in developing end-use markets. Increased understanding of varying biochar behaviour supports recognition of a broader range of environmental and industrial applications. Consequently, a complex system view of pyrolysis biochar value chains has developed (Figure 11-4) recognising a range of valorisation opportunities. A complex systems view recognises dependencies on the place-based context that drives available biomass and valued end-use. The broader value chain is and often referred to the pyrolysis biochar systems (PBS) and includes transport, and infra-structure associated with end-use application. In the context of PyCCS, where offsets are dependent on long-term storage, the permeance of biochar across non-soil applications is less well established.

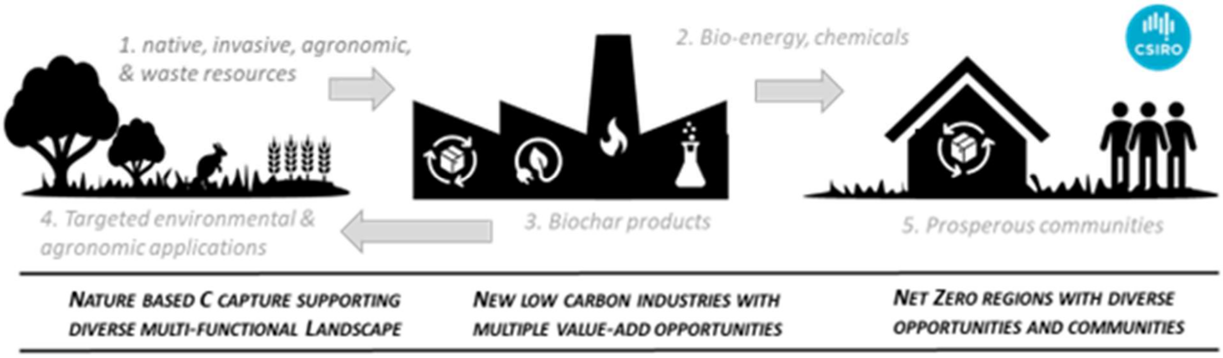



**Figure 11-4: Schematic depicting a complex systems view of the pyrolysis biochar supply chain with multiple points of valorisation. Unlocking the full potential of PyCCS as an offset tool will require consideration of the entire value chain, including local supply and demand logistics, targeted end-use opportunities and associated job opportunities, and gaining social license.**

Durability (or permanence) of biochar is dependent on how it was produced, and where it is used. Long-term durability (>500 years) and a range of co-benefits have been demonstrated in agricultural, environmental, and manufacturing applications. Extensive research on environmental applications includes:

a) as a soil amendment, or an additive to fertilisers / amendments (composts, lime, clay, biologicals) to improve plant productivity, optimise the rate of nutrient release, or support soil health (Schmidt et al 2019, Guo et al 2020);

b) as a sorbent for remediation of soils and water contaminated with organic pollutants (e.g. herbicides, or heavy metals (Ogura et al 2021, Liang et al 2021);

c) incorporation into biomaterials, polymers, and construction materials, with demonstrated value-add benefits associated with strength, durability, or electrical conductivity (Bartoli et al 2022).

Emerging areas of interest for the use of biochar include use as animal feeds to improve health and/or reduce enteric methane production (Man et al 2021) and in catalysing anaerobic digestion (Zhao et al 2021). Biochar is defined as having an end-use in environmental applications, however, the charcoal produced from pyrolysis does attract broader end-use in industrial, biorefinery and energy storage applications (Ramos et al 2022). When the charcoal is used for energy purposes (i.e. burned) there are obviously zero biochar CCS benefits and only benefits in displacement of fossil fuels.

Biochar is included on the IPCCs short-list of negative emissions technologies (NETS) that could provide significant sequestration impact. It is an attractive NET because it relies on the most effective (and lowest cost) method to capture $CO_2$ from the atmosphere (photosynthesis, growth of biomass) combined with a proven technology (pyrolysis) to convert biomass carbon to one of the most stable organic carbon-forms known to persist in the environment for more than 500 years. The offset potential arises directly from the stabilisation of carbon in biochar, and indirectly from its impact on GHG emissions, displacement of fossil fuel use, and carbon sequestration in the end-use environment.

Under Australia's ERF, biochar application to agricultural soil is an eligible activity, representing an avenue for indirect offsets through soil carbon sequestration. Within the ERF proponents must demonstrate an increase in soil carbon over and above the biochar-C added. In 2021 the Australian New Zealand Biochar Industry Group (ANZBIG) provided feedback on this requirement and other method modifications which could be used to support industry development and uptake independently of costly soil carbon verification requirements. Adoption of biochar remains low due to high biochar costs (> $500/t), uncertainty in application outcomes, ability to scale to meet demand, and logistical challenges with transport and emerging value chains.

Biochar is currently listed on voluntary carbon markets (e.g. organisations such as Verra, Puro.earth, Nori, Carbon Future) where biochar-C offsets can be bought and sold. Biochar is expected to garner greater market share owing to comparatively lower uncertainties around the long-term permanence relative to other carbon offset methods. Due to demand for these high-quality carbon credits, biochar-based credits are currently being pre-sold on the voluntary market.

## 11.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt/yr) | Key evidence |
|---|---|---|
| **Technical Potential** | 30-60 | ANZBIG 2020 as below |
| **Economic potential by 2025** | | Defendable estimates are difficult as discussed below |
| **Economic potential by 2035** | | |
| **Economic potential by 2050** | | |

**Table 11-2: Best estimate of biochar sequestration potential**

### 11.3.1 Technical sequestration

Biochar has high technical sequestration with Global sequestration potential estimated at 0.7 – 1.3 Gt $CO_2$ per year (Smith 2016). Many global estimates combine biochar with other NET categories, for example with bioenergy carbon capture and storage (BECCS), or with soil carbon. However, encompassing biochar within soil carbon NETs is problematic as the mechanisms of carbon sequestration, technology considerations, scalability, carbon permanence, and verification pathways differ.

The Australian and New Zealand Biochar Industry Group (ANZBIG) recently estimated the theoretical potential for biochar and bioenergy sequestration in Australia to be:

- 30-60 million metric tonnes of $CO_2$e removal per year (negative emissions)
- 15-30 million metric tonnes of biochar produced per year
- $1.5 and $3.0 billion value in carbon credits

These estimates are based on redirecting 50-100 million metric tonnes of organic residues and wastes from burning and landfill to pyrolysis, and a carbon credit value of ~AUD $48/t $CO_2$e and ~3 t $CO_2$e per tonne biochar as per voluntary market Puro.Earth CORCs June 2020. The wide estimate range (30-60 Mt/y) reflects uncertainty in annual biomass availability under variable climate, and uncertainties in competing uses of biomass resources.

Estimates of indirect carbon sequestration and/or reduced $N_2O$ emissions from use as a soil amendment are more uncertain and often difficult to quantify. Biochar has demonstrated potential to enhance the process of carbon stabilisation in tropical iron-rich soil types (Ferrosols) by forming microstructures with soil minerals and slowing mineralisation of fresh carbon inputs from plant roots (Weng et al 2017).

However, the quantitative importance of this soil-specific mechanisms, and ability to verify small changes at the landscape-scale are difficult to determine.

### 11.3.2 Economic sequestration

Providing defensible estimates of economic sequestration of pyrolysis biochar systems is challenging. Feasibility constraints relate to the availability, logistics, economics, associated with a complex, yet unstable supply chains. Techno-economic assessment of the potential of pyrolysis biochar systems at appropriate regional scales in Australia would generate valuable information to define where in Australia biochar can contribute most effectively towards sustainable low carbon industry development.

## 11.4 Technology Readiness Potential and Commercial Readiness

### 11.4.1 Technology Readiness

| Technology Readiness | \$ per tonne $CO_2e$ | Key Evidence |
|---|---|---|
| **9** | 82 - 119 | See discussion below |

**Table 11-3:Technology readiness assessment for pyrolysis biochar technology**

**Explanation:** The TRL level of pyrolysis technologies used to produce biochar are commonly rated at 9. There are a range of pyrolysis technologies operating at various scales globally, but these tend to be dominated by small to medium scale operations. There are several operational producers in Australia, including trading on the voluntary carbon market through Puro.earth carbon removal certification. The value proposition is not however dependent on carbon credits, with several producers gaining sufficient returns without engagement in the voluntary market. Production quantities across Australia are difficult to ascertain, but there is growing interest in expanding to use a wider range of biomass sources.

### 11.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| **2 - 4** | While there have been trials to date no widespread scaling has occurred |

**Table 11-4: Commercial readiness assessment for pyrolysis biochar technology**

**Explanation:**

There are a number of commercial biochar producers across Australia, but it is difficult to gain information on the scale of production, the commercial propositions, and the associated technical and financial performance. The biochar industry body (ANZBIG), established in 2020, recognises these challenges and will play an important role in improving visibility of industry impact and gaining broader social licence.

In Queensland, Logan Water has established a \$28 M biosolids gasification facility to drive the Councils carbon neutral ambitions. The project is expected to reduce carbon emissions by 6000 tonnes per year, save \$1 M in waste management operational costs, and create new revenue streams from biochar sales. The produced biochar is likely to be used in land applications to support crop productivity and carbon sequestration and provides an exemplar of waste-to-energy solutions with multiple benefits diverting 29,000 tonnes of organic waste from regional landfill, removing 48,000 tonnes of carbon, and generating 600 MWh of renewable energy.

The international biochar market is projected to grow to US$3.1 b by 2025. There are several companies (e.g. PureBiochar, Incept Group) aiming to leveraging international interest and capital investment to become major players in biochar production at industrial scale within Australia within the next few years. For example, PureBiochar aim to open commercial scale be Australia's first industrial scale biochar producer with active commercial operations by end of 2023.

## 11.5 Scalability, Length of storage, Measurement and Verification

### 11.5.1 Scalability.

Globally, the biochar industry tends to have many relatively small producers, although larger-scale operations are emerging in China, the US, and Europe. Centralised pyrolysis biochar facilities are proposed as a key solution in scalability and broad adoption. The European Commission Circular Economy Strategy (2015) note that biochar fits well into a circular bioeconomy approach. Pyrolysis units are available from small-batch-scale (~2000 oven dried tonnes per annum) to large-scale continuous flow (~185,000 oven dried tonnes per annum) operations.

Industrial scale pyrolysis plants have significant logistical and economic advantages but demand continuous high volume biomass supply, and large -scale storage infra-structure. Many biomass resources have seasonal availability, while large-scale purpose specific biomass plantations pose trade-offs with food production, biodiversity, and other sustainable development goals. Co-locating pyrolysis facilities with other biomass and/or waste management facilities provides opportunity to scale biochar production by developing cascading use of biochar within broader circular economy strategies (Schmidt et al 2017).

Networks of smaller-scale units are suggested as a potential pathway that can be effectively integrated as a desired and purposeful co-product of agriculture, aligning with diversified land use (e.g. agro-forestry, silvo-pasture, and perennial cropping). Smaller-scale networks trade-off against logistics, operating costs, and market reach but are proposed suitable where available biomasses are geographically distributed, or seasonally variable.

### 11.5.2 Length of storage

Biochar-C can remain stable in the environment for several hundred years, with mean residence times typically ranging between 300-600 years (Joseph et al 2021) or as long as >1000 years (Lehman et al 2015). For simplicity, we refer to biochar residence as more than 500 years. The stability of biochar is primarily dependent on production technology, temperature and residence times, and the biomasses used. Compared to the raw biomass that decomposes on the annual to decadal timescale (<10 years), biochar is significantly more stable and represents one of the few biomass-derived materials with permanence of > 100 years.

### 11.5.3 Measurement and Verification

The ratio of hydrogen to organic carbon ($H/C_{org}$) is broadly accepted as suitable for quantifying the stable carbon sequestered in biochar. This test is available through commercial environmental and mining analytical labs. High-quality stable biochar has a $H/C_{org}$ of <0.4 and a mean residence time of >1000 years (Lehman 2015). Comparatively plant biomass such as wood or crop residues typically have a H:C ratio of is 1.5, while coal ranges 0.4 to 0.8 depending on its quality and source.

To account for potential decomposition of biochar in the environment, the European Biochar Certificate (EBC) applies an average degradation rate of 0.3% per year (exponential) for biochar in soils. The EBC approach is considered conservative given that many studies demonstrate a small labile pool lost within the first year, followed by persistence of the dominant stable pool.

## 11.6 Social, environmental impacts, risks and co-benefits

### 11.6.1 Social impacts and risks

The main social considerations relating to scaling of biochar pyrolysis systems relate to:

- **Food Security:** in a similar manner to bioenergy, biochar pyrolysis systems should be designed in a manner that does not jeopardise food security by creating tension between land used for food production and for biomass generation. This risk is less likely where waste biomass materials or industrial algal sources used.
- **Community Acceptance:** large-scale pyrolysis biochar systems will need to navigate societal issues relating to perceptions of land use tension for source biomasses and environmental impact, acceptability of centralised location of biomass or waste facilities, and associated impact on local economy, complementary or competing industries.
- **Human Health:** biochar is an irritant to the respiratory system and to eyes and can also contain harmful components as described below (11.6.2). Consequently, risks to human health exist in handling biochar at the point of production through to application. Risks are highest with dry, fine, biochar dusts and can be reduced in post-production processing, such as incorporation into pellets, granules, or composite materials.

### 11.6.2 Environmental impacts and risks

Potential environmental hazards of biochar have recently been reviewed (Xiang et al 2021) and are summarised below. These potential hazards arise from biochar structure and particle size, the presence of harmful components (e.g. heavy metals, polycyclic aromatic hydrocarbon, dioxins, and perfluorochemicals), and biochemical interactions in the environment. However there are Clear risk assessment frameworks that facilitate risk identification and mitigation are needed to build targeted use and industry trust.

- **Contamination:** there are potential risks associated with the use of waste biomass resources that can pose complex regulatory issues and testing. The composition of waste resources can be highly variable but hazards associated with potential contaminants can be managed through existing risk mitigation activities, Australian standards for incineration and handling waste-resources. The IBI provide guidance and standards for the composition of biochar and acceptable limits for use as a soil amendment.
- **Soil Security:** where crop residues are used as the biomass resource for pyrolysis, there is a danger that the land from which this is removed becomes carbon depleted. Crop residues protect the landscape from erosion and drive short term nutrient cycling. Returned to the soil, biochar will perform different functions to crop residues and therefore will not replace the functions of crop residues.
- **Effectivity of agrochemicals:** as a sorbent, fresh biochar can render agrochemicals (e.g. herbicides, pesticides, mineral fertilisers) less effective. This risk is greatest where high rates of fresh biochar are surface applied to soils and can be effectively reduced by low rate, beneath-seed banding, and/or pre-loading biochar with nutrients. For example, used in composting or as a mineral-biochar

composite, the active sites on biochar become saturated prior to application reducing the risk of unintended sorption effects.

- **Environmental fate:** There are potential risks associated with migration of biochar to non-target environments. Biochar is a sorbent for metals, organic, and inorganic pollutants, and is also mobile in the environment subject to wind and water erosion. There are potential risks in it carrying contaminants into non-target environments where they could have toxic impact on sensitive species. While the risk in most environments is likely to be low, improved understanding of the long-term fate of biochar in the environment could be valuable.
- **Ecotoxicity:** Ecological effects have been widely studies, with generally low risks identified. However, biochar can cause stress effects, including mortality, in some organisms. Ecotoxic impacts occur when biochar contains toxic compounds (e.g. heavy metals, polyaromatic hydrocarbons), when it sorbs signal molecules key to organisms physiology and growth, or when it changes available resources such as water and nutrients. For example, there are some limited reports of negative ecotoxicological impact in aquatic organisms, highlighting the importance of quality standards and testing.

Methods for controlling against many of these risks relate to selecting appropriate biomass and biochar types, considering how it will behave in the application environment, and whether there are risks of offsite migration. Frameworks to guide risk assessment in the use of biochar in differing environments, improved understanding of when offsite movement could be problematic, and the ecotoxic impacts in non-target aquatic environments would be valuable for environmental protection and ensuring social license.

### 11.6.3 Co-benefits

The co-benefits from biochar are dependent on the type of biochar produced and context specific factors associated with its end-use. Co-benefits are summarised according to application use below.

- **Soil Amendment:** co-benefits of improved soil condition and function. Benefits depend on the soil-specific constraints that are limiting plant growth and can include direct provision of nutrients, acid neutralising effects, improvement of physical structure and associated moisture use, and changed biological nutrient cycling.
- **Additive to composting systems and/or fertilisers:** co-benefits arise from nutrient retention and reduced emissions of greenhouse gases during composting, reduced time to maturity, and slow-release characteristics that bring benefit to plant growth. Combination with mineral fertilisers has demonstrated slow-release characteristics that can improve fertiliser use efficiency.
- **Supplement for animal feed:** co-benefits have been studies across cattle, goats, pigs, poultry, and fish, and include improved feed conversion to biomass/eggs, immunity, pathogen resistance and toxin removal, and reduction in enteric methane production. Benefits extend beyond the animal itself and into the manure/faecal ‘deposit’ environment, moderating the impact of high nutrient loads. Use of biochar in the animal sector is expected to increase. In Australia there are examples of growers feeding biochar to cattle for economic benefit (Doug Pow WA), and of commercially available biochar enhanced animal feeds (e.g. SoftAgriculture).
- **Landscape management:** eradication of invasive weeds, or manage forestry fuel loads to mitigate wildfire risks, have been suggested co-benefits possible where mobile pyrolysis units are feasible and integrated within a broader pyrolysis biochar systems approach. One Australian biochar producer developed their mobile pyrolysis technology with view to eradicate woody weeds (willow) in Victoria and have since expanded their scope and product range.

- **Remediation & environmental protection:** through use as a sorbent to immobilise heavy metals, inorganic, and organic pollutants and contaminants in terrestrial and aquatic environments.
- **Carbon-Based Composites:** embedding biochar into composite materials can enhance mechanical properties and durability in a range of composites including plastics and construction materials. The global carbon composite market is projected to reach a value of US$130 by 2015.Recognising this application Verra allow non-soil applications that include use in cement and asphalt.
- **Other:** landfill avoidance associated with re-direction of waste resources, value from waste, biosecurity such as elimination of invasive species.

## 11.7 Barriers to implementation:

### 11.7.1 Policy and regulatory environment

The Emission Reduction Fund (ERF) currently recognises the use of biochar as an eligible activity within the "measurement of soil carbon sequestration in agricultural systems method". The method credits new carbon sequestered in the soil resulting from biochar application. The mechanism of biochar-stimulated carbon sequestration has been demonstrated only in iron-rich soil types (Ferrosols) and is unlikely to happen in lighter textured sandy soils or soils without reactive clay minerals. Current government policies do not provide a mechanism to credit the stable carbon within the biochar itself. Biochar offsets within voluntary markets are in high demand due to a lower risk profile associated with the long-term durability of biochar-carbon compared to other credit types (e.g. soil carbon).

A recent ANZBIG scoping paper (2021) highlights the need for broader policy incentives to support mechanisms to drive industry investment and development beyond soil application alone. Accounting for carbon capture and storage potential at the point of production, with eligible end-use activities that are discounted according to the likely permanence/durability could provide an alternative cost-effective approach towards incentives to support C capture and biochar industry development and uptake.

### 11.7.2 Social licence and stakeholder acceptance

In the last decade attitudes towards biochar have been highly divided across many Australian communities. Biochar has suffered legacy perceptions associated with under substantiated claims, over-promise, and unreliable application outcomes generated in emergent years. However, several important developments over this period include the establishment of an industry body (ANZBIG) alongside improved technology, fundamental understanding of biochar behaviour, and demonstrations of how to achieve practical on-farm applications with multiple economic and production outcomes. Alongside emerging carbon markets, pyrolysis biochar systems are gaining acceptance as an integrative pathway to gain value from biomass, capture carbon in a stable form, and support a range of place-specific co-benefits for the environment and communities.

Social licence and acceptance of biochar is intrinsically linked to that of bioenergy, with additional considerations associated with biochar end-use. In bioenergy cropping, trust has been identified as the key variable in gaining social licence to operate and is an under-represented factor in socio-ecological studies of the topic (Baumer et al 2018). Similarly, research to better understand attitudes towards biochar and developed place-based scenarios that help to build evidence and trust will be important to the future of the biochar industry.

### 11.7.3 Technology performance variability

Slow pyrolysis is an established technology, where performance is dependent on biomass and production parameters. Theoretically slow pyrolysis can be optimised to meet the BECCS based benchmark of 90% carbon sequestration efficiency, but at high economic and environmental costs (Smith et al 2015). Carbon sequestration efficiencies of 70-80% are considered realistic for slow pyrolysis between 450°C and 700°C (Schmidt et al 2019).

### 11.7.4 Financial proposition and costs and access to capital

Globally the pricing of biochar has been variable over the past decade largely owing to availability of raw materials. End-use markets for biochar are still not well established leading to considerable uncertainty as to future process. In Australia biochar currently be sourced for about $500/tonne

There is a lack of peer-reviewed published studies on the financial feasibility of biochar. An ANZBIG report on the value of biochar (2019) demonstrates the financial feasibility of several Australian and New Zealand case studies. Acknowledging that the case studies are place and context specific, the report highlights positive financial propositions across farming scenarios including use as an animal supplement, horticultural orchards, potatoes and zucchini production (below). Although carrying varying uncertainties, the case studies demonstrate the type of financial propositions that can be developed at a relatively small-scale.

| Case study | User net benefit (NPV) | NPV per tonne biochar | User cost | Payback |
|---|---|---|---|---|
| **Beef Grazier, WA.<br>[60 head herd]** | $12,000<br>per 60 head herd | $1,700 | $1000 | <1 year |
| **Avocado Orchard, WA<br>[1 hectare, 400 trees, 7 years]** | $20,000<br>per hectare | $400 | $5,040<br>Per hectare | 4 years<br>[first fruiting] |
| **Potatoes, Ballarat NSW<br>[20% fertiliser substitution]** | $8,000<br>per hectare | $53,400 | $160<br>per hectare | <1 year |
| **Zucchini<br>[13 tonnes biochar per hectare]** | $2,400 | $730 | $1,000 | < 1 year |

Table 11-5: Case studies of net costs and benefits for biochar projects. Collated from ANZBIG 2019. Where NPV = net present value

### 11.7.5 Industry supply chains and skills

With very low production rates, current demand for biochar in Australia outstrips supply. Small to medium scale providers dominate production, with products commonly targeted to garden and horticulture markets or use as animal feed supplements. Larger-scale interest and production capacity are growing in Australia, with several industry-scale projects seeking capital investment. Recognising limited supply, some large-scale companies aim to secure early market share in multiple biochar end-use applications by importing biochar in the short term, while establishing their own production capabilities over longer timeframes (e.g. Incept holdings).

As the Australian biochar industry matures from a linear model (Figure 11-3) towards an integrated system (Figure 11-4), supply chain approaches will become increasingly important in building interconnectedness across the stages of production, logistics and end-use. Supply chain analysis will be useful in setting the frameworks for evaluating the economic, social, and environmental dimensions of biochar as a product. Coordinating and managing the flow of materials, information, and finances will be required for an effective and efficient large-scale biochar industry.

### 11.7.6 Market opportunities or market creation

Globally the biochar market was estimated at US$1.3 billion in 2018 and estimated to reach US$3.1 billion by 2025. In Australia, there are significant opportunities to create new low carbon industries around pyrolysis biochar systems, supported by approved protocols and standards such as International Carbon Reduction and Offset Alliance (ICORA). The International Biochar Initiative (IBI) developed a 2014 standards, certification, and carbon protocols for biochar was not approved by ICORA. Further developments are likely to recognise that not all biochar has equal value, and future standards reflect this.

Biochar cardon credits are currently traded on voluntary markets. For example, Puro.earth currently lists 29 carbon removal suppliers, of which 23 are based on biochar. Although dominantly based in Europe and the US, two Australian companies are trading (Jeffries Biochar Operations, ECHO2) with revenue generated from sales being invested in new biochar-based products, expanding production capabilities, and targeting new biomass sources to meet anticipated demand. Similarly, Carbon Futures list 17 carbon suppliers, dominated by biochar producers.

## 11.8 Scaling knowledge gaps:

There has been considerable fundamental research on how different biochar behaves in the environment and how it can be used to support agricultural productivity, remediation, or industrial applications. However, techno-economic and social research is under-represented and could play an important role in focusing Australian research efforts towards informing economic sequestration potential, quantify relevant co-benefits, and garnering social licence. Scaling knowledge gaps include:

1. Based on geographic knowledge of biomass availabilities, how do techno-economic considerations influence sequestration potential and what are the most valued application appropriate to regions and their communities?
2. What are the regionally appropriate supply chain scenarios that allow industry scaling and optimisation to achieve feasible and resilient pyrolysis biochar industry models for the Australian economy.
3. In remediation applications, to what extent is offsite migration of biochar to aquatic environments an issue, and what are the potential impacts of biochar in non-target environments?
4. What is the durability/permanence of biochar-carbon in emerging non-soil-based applications, such as composite materials, industrial catalysis, and in energy storage?
5. How can social licence learnings from other industries (e.g. mining) be used to inform pathways to navigate multiple stakeholder values, balance benefits and trade-offs, and build trust and acceptance of bioenergy and biochar industries.

## 11.9 Chapter References


Amonette JE, Blanco-Canqui H, Hassebrook C, Laird DA, Lal R, Lehmann J, 2021. Integrated biochar research: A roadmap. Journal of Soil and Water Conservation 76(1), 24-29.

Bartoli M, Arrigo R, Malucelli G, Tagliaferro A, Duraccio D, 2022. Recent Advances in Biochar Polymer Composites. Polymers. 14(12).

Blackwell P, Krull E, Butler G, Herbert A, Solaiman Z, 2010. Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. Australian Journal of Soil Research 48, 531-45.

Guo XX, Liu HT, Zhang J, 2020. The role of biochar in organic waste composting and soil improvement: A review. Waste Management 102, 884-99.

Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, et al, 2021.How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. Global Change Biology Bioenergy 13,1731-64.

Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, et al. 2021. Biochar in climate change mitigation. Nature Geoscience, 12, 883-+.

Liang LP, Xi FF, Tan WS, Meng X, Hu BW, Wang XK, 2021. Review of organic and inorganic pollutants removal by biochar and biochar-based composites. Biochar 2, 255-81.

Man KY, Chow KL, Man YB, Mo WY, Wong MH, 2021. Use of biochar as feed supplements for animal farming. Critical Reviews in Environmental Science and Technology 51, 187-217.

Ogura AP, Lima JZ, Marques JP, Sousa LM, Rodrigues VGS, Espindola ELG, 2021. A review of pesticides sorption in biochar from maize, rice, and wheat residues: Current status and challenges for soil application. Journal of Environmental Management 300.

Ramos R, Abdelkader-Fernandez VK, Matos R, Peixoto AF, Fernandes DM 2022. Metal-Supported Biochar Catalysts for Sustainable Biorefinery, Electrocatalysis, and Energy Storage Applications: A Review. Catalysts 12.

Schmidt HP, Anca-Couce A, Hagemann N, Werner C, Gerten D, Lucht W, et al. 2019. Pyrogenic carbon capture and storage. Global Change Biology Bioenergy, 11, 573-91.

Schmidt HP, Kammann C, Hagemann N, Leifeld J, Bucheli TD, Monedero MAS, et al. 2021. Biochar in agriculture - A systematic review of 26 global meta-analyses. Global Change Biology Bioenergy, 13, 1708-30.

Smith P,2016. Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22, 1315-24.

Wang CQ, Luo D, Zhang X, Huang R, Cao YJ, Liu GG, et al. 2022. Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. Environmental Science and Ecotechnology, 10.

Weng Z, Van Zwieten L, Singh BP, Tavakkoli E, Joseph S, Macdonald LM, et al. 2017. Biochar built soil carbon over a decade by stabilizing rhizodeposits. Nature Climate Change, 7, 371-+.

Xian L, Liu S, Ye S, Yang H, Song H, Qin F, et al. 2021. Potential hazrds of biochar: The negative environmental impact of biochar applications. Journal of Hazardous Materials 420, 12661.

Zhao WX, Yang HZ, He SF, Zhao QL, Wei LL. 2021 A review of biochar in anaerobic digestion to improve biogas production: Performances, mechanisms and economic assessments. Bioresource Technology, 341.

# 12 Geological Storage

| Emission Type | Avoided | Negative |
|---|---|---|
| Enabling Capture Technology | Biological | Engineered |
| Enabling Storage Technology | Biological | Engineered |

**Figure 12-1: Geological storage technology type**

Geological storage of $CO_2$ is described as the process of transporting and injecting the $CO_2$ into suitable geologic reservoirs, typically around 2000m below surface. The technology is typically referred to as carbon capture and storage (CCS). This report is focused on geological storage only, however, as most literature refers to CCS as a whole, the term CCS is generally used throughout the text. It is important to note that the "S" in both BECCS and DACS (discussed elsewhere in this report) stands for the geological storage of CO2 as described herein chapter 12. BECCS and DACS require permanent storage of the CO2 produced or captured as part of their processes and geological storage remains the most viable option.

Recently, the term CCUS has been widely used. The U stands for Utilisation and refers to either the direct of use of CO2 (such as in food preservation and beverages) or indirect use where the CO2 is converted or used to produce other high value goods. For example, $CO_2$ can be combined with reactive minerals to form solid products useful for construction or mine rehabilitation. There are also several other utilisation options, including conversion into fuels, plastics and other products. Not all of these products provide permanent storage but may have the secondary benefit of displacement of their fossil carbon-based equivalents. A discussion of these options is out of scope for this report.

In many other countries, including the USA and Canada, $CO_2$ is injected into depleted oil reservoirs for the purpose of producing more oil, a technology called enhanced oil recovery (EOR). During EOR, the $CO_2$ is injected into the reservoir, mixes with the oil and carries it up to the surface. Once at the surface, the oil is separated, and the CO2 is re-injected producing a cyclic, closed system. EOR projects are not designed for CO2 storage, however, a portion of the CO2 will remain trapped in the reservoir. The volume of CO2 trapped varies for each reservoir but is generally considered to be 30-40% (Whittaker and Perkins, 2013). EOR technology is not currently used in Australia. However, the decades of experience and expertise gained from $CO_2$ transport, injection, and monitoring in EOR fields are applicable to geological storage and demonstrates the maturity of the technology. Utilisation of $CO_2$ in EOR or applications other than geological storage are not currently eligible to generate ACCUS (Australian Carbon Credit Units).

## 12.1 Summary

**Description and current uptake**

Geological storage is the final part of the carbon capture and storage (CCS) process. Once captured, carbon dioxide ($CO_2$) is transported and injected into permeable rock layers. Transport is usually by pipeline or ship. At injection sites, the $CO_2$ is compressed into a supercritical fluid (with density less than water but greater than gas) and pumped into a suitable geological formation. The storage reservoir (typically a sedimentary rock, such as sandstone) is overlain by sealing rocks (typically low permeability mudstone or shales).

Among the reservoirs suitable for $CO_2$ storage, two types most applicable for Australia are depleted oil or gas fields and saline aquifers. There are currently several projects in different stages of development around Australia, including Australia's only operating CCS project, Gorgon, which started operation in August 2019 and has stored more than 6.6M in that time. Based on publicly available data, the combined Australian projects have an announced total capacity of ~30 Mt $CO_2$ per year. Santos' South Australian Moomba Project is scheduled to begin injection in 2024, with planned storage volumes of 1.7 Mt per year and a 25-year crediting period (Santos, November, 2021).

**Sequestration potential**

**Technology readiness potential and commercial readiness**

Development of oil and gas resources has resulted in extensive and detailed knowledge of both the subsurface and fluid migration, accumulation and containment. All of this technological expertise can be applied to geological storage.

Subsurface fluid accumulations such as oil, gas and $CO_2$ are known to occur naturally and to have been in place for many millions of years. The subsurface storage of fluids is a mature and well understood technology.

CCS projects have reached the operational stage in several places around the world. In 2021, the combined pipeline of global CCS projects were estimated to total 111 Mt per year. CCS is often termed a "failed technology", however there are a range of reasons a project does not or may no longer match the business needs of the proponent. This is not failure, it is part of the standard decision-making process. For example, some previous "failures" of CCS projects have been associated with the significant costs associated with retrofitting existing coal fired power stations. There is no documented evidence of the storage component of these projects being the deciding reason the projects did not go ahead. Some projects have been abandoned due to lack of social license (Germany) and considerations of cost and risk (BP, offshore Vlaming). In addition, proposed projects may be deemed to be non-economic but become economically viable as market forces change.

There is one example of the storage component causing a project to stop prematurely, the In Salah project in Algeria. During injection injecting into the thin low permeability reservoir, the lower caprock show evidence of fracturing, noting that the whole caprock sequency was 950m thick. Although the conclusion was that the formation can sustain a breakdown of lower caprock units without compromising the overall storage integrity, this halted CO2 injection and the project.

**Scalability, length of storage, measurement and verification**

Saline aquifers generally have a much larger storage capacity than needed for a particular project; consequently, a storage facility may be able to expand cost effectively if additional $CO_2$ sources come online at a later date. Hence, storage is highly scalable. The length of storage is the same for the natural accumulation of hydrocarbons, which is known to be for millions of years. Monitoring and verification of injected $CO_2$ uses standard engineering tools and techniques and is highly precise.

For geological storage, the major costs are associated with compressing and transporting $CO_2$ to the storage site. There are additional costs with identifying a suitable geological storage site. For example saline aquifers this will require seismic surveys and to drill at least one well; in contrast depleted fields may not need additional seismic but existing wells and infrastructure may need expensive recompletion or remediation. Because of these, CCS is better suited to large or multiple emission sources as a hub.

**Social, environmental impacts, risks, and co-benefits**

Geological storage is managed by applying rigorous, well established methods and regulations. However, some social concerns remain: CCS is seen by some as enabling and prolonging the use of fossil fuels and delaying the uptake of renewable energy; communities worry about issues of well integrity, groundwater contamination and emissions leaking from pipelines. Any onshore development in Australia needs to consider Traditional Owners and all other stakeholders.

The risk of environmental impacts from geological storage of CO2 is very low. Project sites are selected to avoid loss of $CO_2$ and any interaction with groundwater resources. Due to the depth of storage, the likelihood of injected $CO_2$ reaching the surface is very low. The surface footprint of storage projects is very small (wellheads, well pads and access roads) but pipelines may be required to run over several hundred kilometres. While hazardous at high concentrations, CO2 is not a toxic substance and is common in our everyday lives.

There is considerable discussion about low emission industrial hubs. These hubs may include CCS along with hydrogen and manufacturing industries supported by renewable energy. The combined social and environmental impacts, risks and co-benefits of each hub and the industries it contains will be an important factor in their development.

Positioning Australia as a clean energy supplier and/or storage site for regional $CO_2$ emissions may have a range of socio-economic and geopolitical co-benefits. There are local employment opportunities for many industries at all stages of project development, for industry specialists (such as geologists and engineers) and general service providers (such as restaurants, hotels and local retail).

**Barriers to implementation**

There are a number of regulatory bodies involved in $CO_2$ transport and geological storage (both onshore and offshore) and barriers to implementation are not technological. However, stakeholder acceptance and social licence are important considerations. While the technology may be perceived to support the fossil fuel industry, there are also arguments that it may have positive economic aspects and may help abate emissions from industries where sequestration is difficult. Australia is one the largest global exporters of liquified natural gas (LNG) and there is a growing imperative to account for the Scope 3 emissions associated with these exports.

Currently, CCS is capital intensive. The highest risk associated with CCS is the economic risk that once investment occurs, the storage container is either too small or the injectivity is insufficient to justify the capital investment. New business models are exploring how to offset costs and generate revenue by providing a storage service for multiple emitters delivering $CO_2$ to a single ‘hub’.

The CER Carbon, Capture and Storage Method allows a crediting period of 25 for CCS projects to recognise the very large upfront and ongoing costs, and the fact that they are not expected to generate any revenue other than ACCUs.

**Scaling knowledge gaps**

The technological challenges for deployment of geological storage are associated with finding ways to reduce costs by optimising storage capacity. A second challenge is reducing the time taken to characterise a potential storage site to a sufficient confidence level for regulators, project operators and communities.

A summary of CCS technology is provided in Figure 12-2.

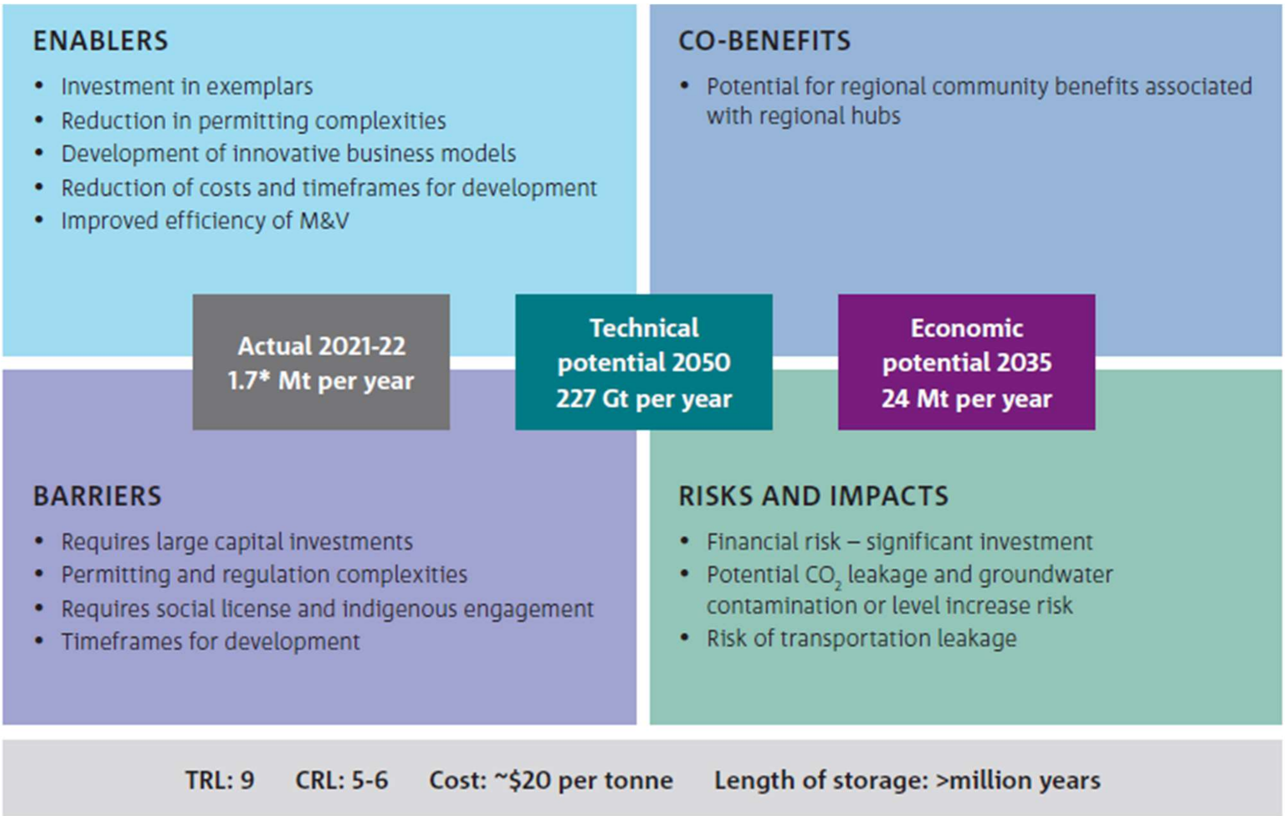



Figure 12-2: Summary of geological storage. *estimated for the Gorgon project since commencement in 2019.

**Case study:** Northern Lights Project, Norway

The Norwegian Northern Lights project is a full-scale CCS project called "Longship". The full-scale project includes capture of CO2 from industrial sources in the Oslofjord region (cement and waste-to-energy) and shipping of liquid CO2 from these industrial capture sites to an onshore terminal on the Norwegian west coast. From there, the liquified CO2 will be transported by pipeline to an offshore storage location subsea in the North Sea, for permanent storage. Phase 1 includes capacity to transport, inject and store up to 1.5 million tonnes of CO2 per year. The facilities are scheduled to be operational in 2024.

## 12.2 Description and current uptake

Geological storage of $CO_2$ is described as the process of transporting and injecting the $CO_2$ into suitable geologic reservoirs, typically around 2000m below surface. The technology is typically referred to as CCS, carbon capture and storage. This report is focused on geological storage only.

The $CO_2$ is captured either from stationary sources (such as coal or gas fired power plants, cement production or steel manufacturing), including bioenergy facilities (see BECCS, Section 1313) or more recently, directly from the atmosphere (Direct Air Capture (DAC), see Section 14).

Once captured, the $CO_2$ is transported to the injection site. Transport can be either by pipeline or ship. Transport by truck is possible, but the volume is too small to be economically viable. At the injection site the $CO_2$ is compressed and pumped into the subsurface via an injection well. Before injection, the $CO_2$ is dehydrated and compressed into a supercritical fluid. Injection as a supercritical fluid enables the maximum amount of $CO_2$ to be stored at the storage site while still maintaining injectivity. The most significant costs associated with storage are related to the costs of compression, dehydration and transport (Figure 12-8). Therefore, minimising the distance between the “source” of $CO_2$ and the “sink” is a primary goal of geological storage.

The storage container consists of a reservoir, typically a sedimentary rock (such as sandstone) overlain by sealing rocks, typically low permeability mudstones or shales. The $CO_2$ is stored in the pore spaces between the grains in the sandstones and prevented from moving vertically by the impermeable seal rocks. The extent and distribution of the plume of $CO_2$ in the subsurface is monitored by an array of downhole and surface monitoring tools for the purposes of both assurance and verification. The injection lifetime of a project is typically of the order of 30 years and the volumes of $CO_2$ between 1-5 Mt per year. Monitoring and verification will continue for several decades, post injection.

The selection of a suitable site is the first step and the most critical part of any project development. For example, proximity to groundwater or other hydrocarbon resources may eliminate a prospective site. Faults are of particular importance as they can act either as barriers to constrain the size of the container, hence limiting the capacity, a conduit to another reservoir, or have no impact at all. Faults are common geological features and for the most part, are small with no impact. Faults and fault behaviours are well-studied for their influence on subsurface fluid flow. Very few provide potential pathways to surface and those that do are easily detected with standard exploration tools. Consequently, consideration of faults are a key consideration when siting CCS projects. Wells (injection, monitoring and legacy) are a recognised risk of vertical migration of small volumes of $CO_2$. Selection of a site includes detailed consideration of the risks posed by wells. In Australia there are extensive regulations around construction, monitoring and mitigation strategies.

There are several types of reservoirs suitable for storage, but there are two that are most applicable to Australia. The first is storage in depleted hydrocarbons fields where secure containment of hydrocarbons has been maintained by the geological structures for many millions of years. These projects have the advantage of the vast amount of geological knowledge acquired through the production of the oil or gas that was originally in place. They also have existing infrastructure, some of which may be suitable for repurposing for $CO_2$. However, this also represents an additional risk as the infrastructure in some cases will be old and no longer fit-for-purpose.

The second option is saline aquifers. These are reservoirs with no economic resources, such as oil, gas or water. Saline aquifers have vast amounts of storage potential, however, are largely unexplored. This makes their development potentially more costly due to the greater uncertainty of finding suitable storage intervals.

Once injected, the $CO_2$ will remain in place for many millions of years. The permanent storage of the injected $CO_2$ can be compared to the accumulation and containment of other fluids in the subsurface, including naturally occurring $CO_2$. For example, the Buttress Field in Victoria contained a natural accumulation of $CO_2$ for many millions of years before being produced at surface and processed into food grade $CO_2$. There are several fields in Victoria and other parts of Australia and the world where C $CO_2$ has accumulated and been stored for many millions of years.

There are a number of projects in different stages of development in Australia. These are described in Table 12-2 and the locations are shown in Figure 12-3 . Generally, for geological storage, global uptake is increasing (GCCSI, 2021).

## 12.3 Sequestration potential

| Estimate of sequestration | Sequestration ($Mt.yr^{-1}$) | Key evidence |
|---|---|---|

| | | |
|---|---|---|
| **Technical Potential** | 227 Gt | Compiled by GA from publicly available data, Table 12-2 |
| **Economic potential by 2025** | | |
| **Economic potential by 2035** | ~24 | From estimates of projects under development Table 12-2 below. |
| **Economic potential by 2050** | >50 | Is an estimate based on doubling the 2035 estimate. |

**Table 12-1: Best estimate of geological sequestration potential**

Australia has significant geological storage potential due to the suitability of our geological basins for $CO_2$ storage, many of which are close to industries that emit highly concentrated streams of pure $CO_2$. There is more than enough theoretical capacity to account for Australia's emissions and potentially those of the region.

Since 2009, there have been several assessments of Australia's $CO_2$ storage potential at the national, basin and specific storage site scale. A national and basin scale assessment of Australia's potential and capacity to transport and store $CO_2$ was completed in 2009 for the Carbon Storage Taskforce (under the National Low Emissions Coal Initiative - NLECI), to produce the National Carbon Mapping and Infrastructure Plan (NCMIP). The high-level assessment took into consideration geological characteristics and other factors to determine the potential, capacity and ranking of sedimentary basins for $CO_2$ geological storage. Since this report was published there have been several basin specific studies undertaken by Geoscience Australia, CSIRO, CO2CRC and others. There are also specific storage site assessments undertaken by oil and gas companies in areas aligned with their commercial interests, for example, Chevron for the Gorgon Project, INPEX for the Petrel sub-basin. In addition, some states have completed their own assessments. For example, the West Australian Department of Mines and Energy published the Western Australia Carbon Dioxide Geological Storage Atlas in 2013; the Queensland Government's Queensland CO2 Geological Storage Atlas among others.

A compilation of the theoretical storage capacity from the studies is shown in Table 12-3. Theoretical (or the equivalent term potential as is used in this report) storage capacity is the absolute maximum capacity estimate based on geology alone and can be orders of magnitude greater than the practical storage capacity required for a specific project. Nevertheless, the sum of these high-level storage assessments is 227 Gt, excluding depleted oil and gas fields. While the theoretical capacity is large, most of it will not prove to be useful for reasons other than the geological constraints. This includes factors such as cost, access to infrastructure, resource competition and social acceptance, among others. This is the same for both nature based and engineered solutions.

The Gippsland, Surat, and Cooper Basins, together with the Petrel and Barrow sub-basins host carbon storage sites at an advanced stage of development, and each have genuine industry interest and support (Figure 12-3). The combined storage capacity at four of these key locations alone (Gippsland, Surat, and Cooper Basins, and the Petrel sub-basin) is over 20 billion tonnes (20 Gt) (LETS, 2021).

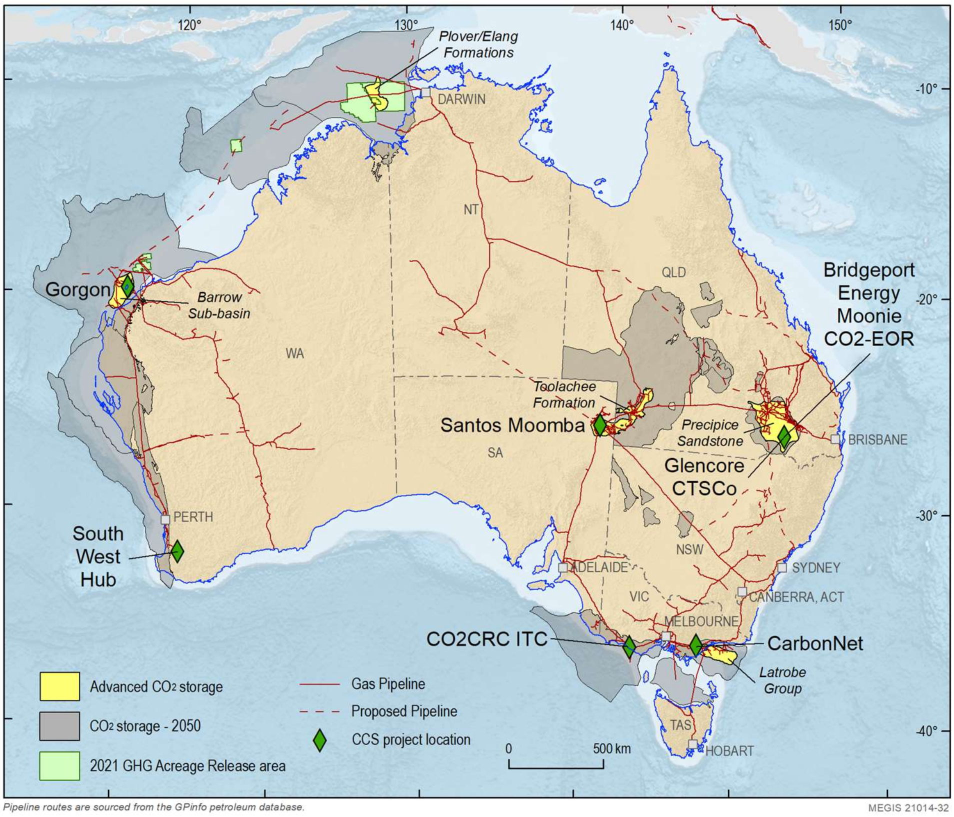



**Figure 12-3: CCS sites in advanced stages of development. (LOW EMISSIONS TECHNOLOGY STATEMENT 2021 Australian Government Department of Industry, Science, Energy and Resources)**

| Basin | Sub Basin/Region | Saline Aquifer $CO_2$ storage estimation in Gt | | | | |
|---|---|---|---|---|---|---|
| | | National Assessment (NCIMP P90) | | Regional Assessment | | |
| | | Offshore | Onshore | Offshore | Onshore | Storage Formation |
| Bass | | 12.7 | | 0.4 | | Eastern View Group |
| Bowen | | | 1.6 | | 0.4 | 0.1Gt Aldebaran Sst, 0.2Gt Showground Sst, 0.09Gt Tinowon Fm |
| | Denison Trough | | 1.7 | | 0.5 | |
| Browse | | 7.0 | | | | |
| | Caswell Sub-Basin | | | 0.1 | | 0.1Gt Caswell Fan Complex |
| Bonaparte | | 32.2 | | | | |
| | Petrel Sub-Basin | | | 15.8 | | 6.5Gt Plover Fm, Elang Fm and lower Frigate Sh, 9.3Gt Sandpiper Sst |
| Canning | | 23.5 | 16.5 | | 1.9 | 0.8Gt Anderson Fm, 0.3Gt Grant Group, 0.7Gt Willara/Nambeet Fm, 0.06Gt Virgin Hills |
| Carnarvon north | | 25.5 | | | | |
| Carnarvon south | | 11.1 | | | 0.1 | 0.01Gt Birdrong/Wogatti, 0.04Gt Lyons Group |
| Clarence-Moreton | | | 2.9 | | | |
| Cooper | | | 4.1 | | 0.172 | Toolachee Fm |
| Darling | | | 2.6 | | 0.6 | |
| Eromanga | | | 11.6 | | 46.413 | 20.2Gt Wyandra Sst, 6.5Gt Adrori Sst, 12.2Gt Hutton Sst, 5.5Gt Hooray Sst, 2.1Gt Lower Poolowanna Fm |
| Galilee | | | 7.5 | | 3.4 | 0.6Gt Betts Creek Beds, 1.5Gt Clematis Sst, 1.3Gt Colinlea Sst |
| Gippsland | | 30.1 | 0.7 | >10 | <0.1 | Latrobe Group |
| Gunnedah | | 0.4 | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | 1.3Gt Lesueur Sst, 0.04Gt Beekeeper Fm, 0.006Gt Dongara/Wagina Fm |
| | | | | | | |
| Surat | | | 6.1 | | 2.97 | 1.3Gt Precipice Sst, 0.02Gt Basal Evergreen Unit, 0.5Gt Boxvale Member, 1.2Gt Hutton Sst |
| | | | | | | |
| Sydney | | | 0.4 | | | |
| | | | | | | |

**Table 12-2: Regional estimates for the Bowen, Surat, Eromanga, Cooper and the Galilee Basins are from the QLD $CO_2$ Storage Geological Atlas (2009). WA Atlas (2013) provides regional $CO_2$ storage estimates for the Canning, Perth and the Carnarvon Basins. The Caswell Sub-Basin, Petrel Sub-Basin and the Gippsland Basin regional estimates are from the relevant NCIP study. Denison Trough regional estimate is from ZeroGen (2014) study. Note that some basins, despite having an associated capacity estimate, are not considered prospective due to their geological characteristics (e.g. the Sydney Basin).**

There are several projects in different stages of development in Australia and several in the ASEAN region. The figure and table below provide a summary of the current Australian projects based on publicly available data. The storage potential for most of these projects has not yet been made public, however, the combined total announced storage rate is ~24 $Mt.y^{-1}$. It is important to note that for these projects the capacity is not limited by the geology, but the volumes produced by the $CO_2$ source and the pipeline dimensions. In most cases of saline aquifer storage, the aquifer has significantly more capacity than the project requires, enabling future expansion if needed.

The 2021 Greenhouse Gas Storage Acreage Release opened for bidding in March 2022. The 2021 release comprises five areas located across three sedimentary basins in Commonwealth waters offshore of Western Australia and the Northern Territory. These five areas have now been awarded (as of end August 2022) based on work program bids, and this information is now publicly available here: https://public.neats.nopta.gov.au/Title (search for “greenhouse gas”).

The CER CCS Methodology was approved in 2021. There is currently one registered project, Santos’ Moomba Project. Injection is scheduled to begin in 2024 with a crediting period of 25 years. The project proposes to store 1.7 million tonnes per annum (Mtpa) at a full lifecycle cost of less than US$25 per tonne and operating costs of US$6-8 per tonne (Santos, November, 2021). Chevron’s Gorgon Project does not meet newness requirements under CER regulations and is therefore not eligible for ACCUs.

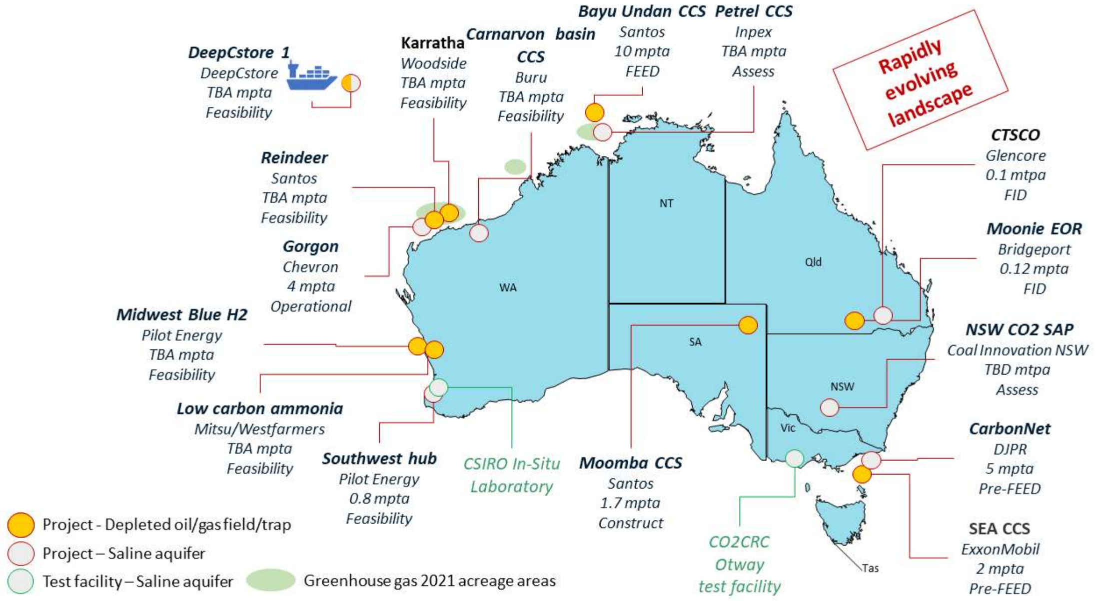



**Figure 12-3: Location of CCS projects in the pipeline in Australia, October 2022.**

| Project | Proponent | Storage Type | Sequestration Rate Mt.yr $^{1}$ (total) | Status |
|---|---|---|---|---|
| **DeepCStore 1** | DeepCstore | Saline aquifer | 5 | Feasibility study |
| **Reindeer** | Santos | Saline aquifer | 2.4 | Feasibility study |
| **Gorgon** | Chevron | Saline aquifer | 4 (120 M) | Operational |
| **Midwest Blue H2** | Pilot Energy | Saline aquifer | TBA | Feasibility study |
| **Low Carbon Ammonia** | Mitsui/Wesfarmers | Depleted reservoir | TBA | Feasibility study |
| **Southwest Hub** | Pilot Energy | Saline aquifer | 0.8 | Feasibility study |
| **Moomba CCS** | Santos | Depleted reservoir | 1.7 (85 M) | Construction phase |
| **SEA CCS** | ExxonMobil | Depleted reservoir | 2 | Preliminary front-end engineering design (Pre-feed) |
| **CarbonNet** | DJPR | Saline aquifer | 5 (125 M) | Pre-feed |
| **NSW CO2 SAP** | Coal Innovation NSW | Saline aquifer | TBA | Site Assessment |
| **Moonie EOR** | Bridgeport | EOR | 0.12 | Financial Investment Decision (FID) |
| **CTSCo** | Glencore | Saline aquifer | 0.06 (0.18 M) | FID |
| **Petrel CCS** | INPEX | Saline aquifer | TBA | Site Assessment |
| **Bayu-Undan** | Santos | Depleted reservoir | 10 | Front-end engineering design (FEED) |
| **Carnarvon Basin CCS** | Buru | Saline aquifer | TBA | Feasibility study |
| **Karratha** | Woodside | Depleted reservoir | TBA | Feasibility study |

| | | |
|---|---|---|
| | | |
| **TOTAL** | **16** | **23.72** |

Table 12-4: Geological storage projects in Australia at various stages of development.

An estimate for economic potential sequestration for 2035 can be provided by summing projects under development which is 24Mt per year (Table 12-2). Costs can be estimated between $14 to $35 per tonne (excludes capture, but includes transport and injection, figure 12.8) based on the APGT Report, 2015.

## 12.4 Technology Readiness Potential and Commercial Readiness

The annual status of CCS report prepared by the GCCSI (Global Institute of CCS) tracks the development of CCS projects across the world. In addition to the increased number of projects in Australia with a combined storage rate of up to 25 Mtpa (see previous section), the report notes the combined storage rate of global CCS projects under consideration has grown from 75 Mtpa at the end of 2020 to 111 Mtpa at September 2021, a 48% increase (GCCSI Global Status Report, 2021). This provides clear evidence that the technology works and can be economically viable.

### 12.4.1 Technology Readiness

| Technology Readiness | $ per tonne $CO_2e$ | Key Evidence |
|---|---|---|
| **9** | 20 | Australian Government LETS (Low Emission Technology Statement) stretch target for transport and storage |
| | 30 | Santos Moomba project |
| | ? | Operating projects in Australia (Gorgon) and the Netherlands (Snovit) |
| | 15 -35 | AGPT 2015 - Transport and storage costs, assumes costs of electricity and varies according to the length of pipeline. Note publication is from 2015 and excludes the cost of capture (Figure 12-8) |
| | | Quest (Canada), 1Mtpa/4 years |

Table 12-5: Technology readiness assessment

**Explanation:**

CCS has reached operational stage in several projects around the world (GCCSI status report, 2021). Figure 12-4 is indicative of the global storage potential and Australia is one of the highest. Figure 12-4 also indicates the level of global interest in the technology. The yellow bars are indicative of the interest each country has in exploring it's own resources as they map their own transition toward reducing emissions. Note, Figure 12-6 does not comment on the maturity or accuracy of these assessments.

Geological structures have been accumulating and storing vast amounts of fluids in the form of oil and gas for many millions of years. Anthropogenic development of these resources has resulted in extensive and detailed knowledge of the subsurface, including the mechanisms of fluid migration, accumulation, and containment. The oil and gas industry has developed highly sophisticated tools for finding, measuring, and producing subsurface fluids. Much of this expertise is available for application to geological storage.

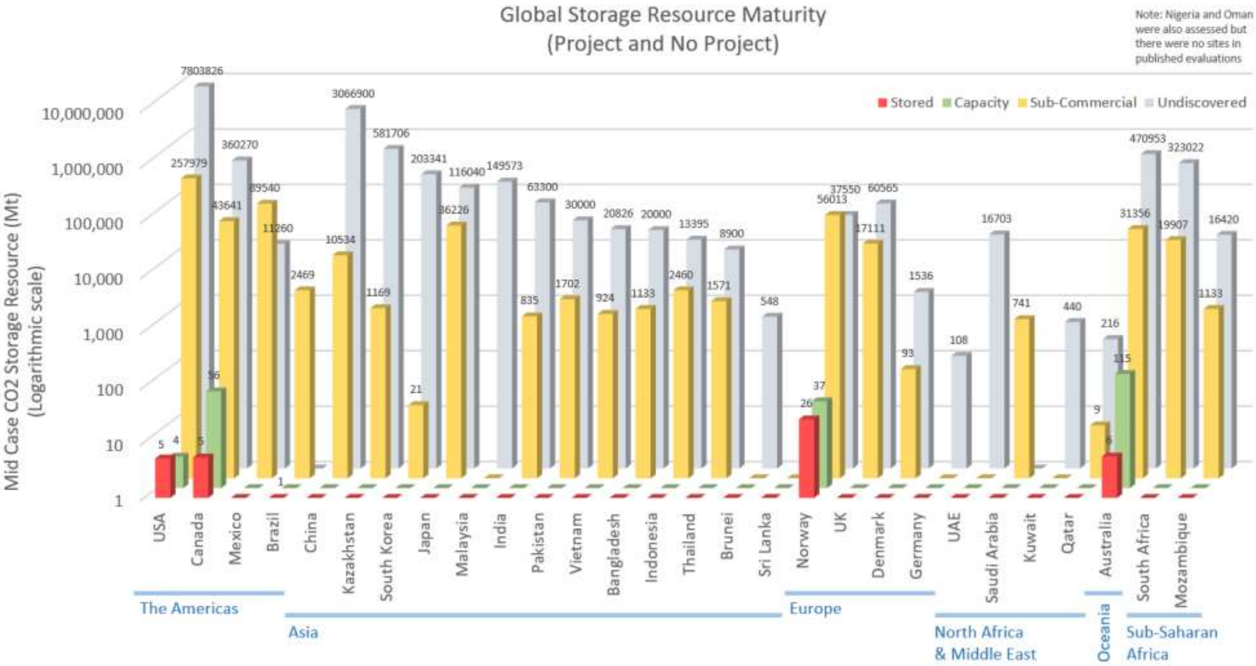



**Figure 12-4: Plot of global storage resources and resource maturity from the GCCSI CSRC database. (Figure taken from the $CO_2$ Storage Resource Catalogue Cycle 3 Report, March, 2022, published by OGCI, GCCSI and Storegga).**

## 12.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| 5-6 | Technology is developed however the commercial imperative is not yet present in Australia. In other parts of the world, for example, US where there are tax incentives for $CO_2$ storage there is increasing competition for CO2 sources and multiple storage sites in development (The Big Business of Burying Carbon \| WIRED; Pers. Comm. BEG, Texas)<br><br>Global CCS project pipeline has grown from 75 Mtpa at the end of 2020 to 111 Mtpa at September 2021, a 48% increase (GCCSI Global Status Report) |

**Table 12-6: Commercial readiness assessment for carbon capture and storage**

The Gorgon Project offshore Western Australia is the only commercially operating project in Australia. It is the first of its kind and the largest storage project in the world to date. It has stored more than 6.6M tonnes since it began operations in 2019 and is planning to increase the injection rate to reach capacity in 2023 (note this information is from multiple Chevron presentations). The location of the facility on an island and Class A nature reserve added significantly to the time and cost associated with the development of the infrastructure for the project. At the time of development, it was the largest CCS project in the world and the first for Australia. Both factors contributed to delays and cost over runs and contributed to the project being behind its target storage volume. Nevertheless, the bespoke Barrow Island Act has been successful applied to regulating the project and identifying/addressing operational issues. For example, the project is currently experiencing technical issues associated with the disposal of wastewater produced from injecting

$CO_2$. This is not an unusual problem for conventional petroleum production and techniques to address the issue are being applied, overseen by the regulator.

The Otway International Test Centre (OITC) in the Otway Basin of Victoria (OITC) is one of the world's most important storage sites where 60,000 tonnes of CO2 have been stored for 15 years and is still monitored to demonstrate the CO2 has been stored safely and securely. An additional 30-40,000 tonnes of CO2 have been successfully injected, stored and monitored in subsequent injections and provides ongoing confidence in CCS technologies. In this respect, the OITC has been running successfully as a small-scale storage as well as research project.

## 12.5 Scalability, Length of storage, Measurement and Verification

In summary, geological storage provides storage of $CO_2$ for millions of years, is scalable to many millions of tonnes per year and is supported by robust monitoring and verification technologies.

### 12.5.1 Scalability.

CCS is more easily applied to large projects, where the volume of $CO_2$ to be stored is significant, for example, greater than 1 M/per year. This is because of the large capital investment required for the compression, transport, and storage, separate from the costs associated with capture. There is considerable investment required to prove a site is suitable for storage, with the minimum requirement being seismic surveys and at least one well. The costs onshore are less than for offshore.

The capital-intensive nature of CCS project presents a problem for smaller emitters (of the order of few hundred thousand tonnes per year) as they cannot afford the infrastructure investment of pipelines, wells etc. Hence, there is a growing interest in the concept of integrated CCS hubs and the associated innovative business models required to make these investable. There are several examples in development, many associated with H2, for example, Teesside in the US (United States), Tomakomai in Japan and the previously described Northern Lights project. (This is discussed in more detail in 3.6.4)

Even accounting for the fact that not all of the pore space available can be practically accessed, it is important to note that the storage capacity of saline aquifers is generally much larger than the specific capacity developed through a particular project. Hence the difference between basin scale assessments and site-specific assessments. This means that a particular storage facility may have the ability to cost effectively expand the storage capacity if additional sources of $CO_2$ come online.

### 12.5.2 Length of Storage.

The length of storage is analogous to the accumulation of hydrocarbons and is of the order of millions of years. However, for practical purposes, the Intergovernmental Panel on Climate Change's (IPCC, 2005) original estimate of storage security suggests that a successful project would achieve 99% retention of stored CO2 for at least a thousand years. This is supported by further research and by extensive examination of natural accumulations of CO2. For example, a study by Kamman 2016, showed that there was no evidence of cap rock corrosion for 100,000-year-old CO2 reservoirs, suggesting CO2 had been successfully contained and would continue to be contained.

### 12.5.3 Measurement and Verification

The measurement of the volume of $CO_2$ being transported and at the point of injection uses standard engineering tools and techniques and is highly precise with very low detection levels (ppm or ppb depending on the tool). Losses at the surface through infrastructure leaks (such as pipelines and well heads) is minimised and remediation technologies applied when emissions are detected. There has been significant work undertaken to develop mitigation technologies, for example, the European MiReCOL (Mitigation and Remediation of CO2 Leakage) project (Brunner and Neele, 2017). Remediation strategies are also part of the regulatory requirements. Transport of $CO_2$ through pipelines and injection through wells is common practice in the USA and other parts of the world.

Monitoring and verification of the injected $CO_2$ plume volume and dimension is through the highly sophisticated subsurface imaging technology developed in the oil and gas industry. This includes 4D time-lapse seismic monitoring and pressure monitoring coupled with dynamic simulations of fluid acoustic properties. It is essential for the commercial and regulatory arrangements that there is demonstrable verification of the stability (or otherwise) of the injected plume. In addition, there is ongoing research and field trials to enable the quantitative visualisation of $CO_2$ plumes in the subsurface of up to a few thousand tonnes. This level of precision will provide regulators and stakeholders with quantitative data on the movement and location of the plume of injected $CO_2$ as it moves away from the injection point.

All projects will be required to have comprehensive monitoring and verification programs over the lifetime of the project. Additional monitoring will be required post-closure, i.e., after injection has ceased and the project is completed. The period of time for post-closure monitoring varies but in the USA is the order of several decades. Mitigation strategies in the event of an unexpected migration from the primary container are part of the approvals process for any project.

## 12.6 Social, environmental impacts, risks, and co-benefits

Geological storage is managed to be safe by the application of rigorous and well-established methods. The hierarchy of steps towards achieving a safe project is captured in the “safety and security” pyramid (see below, Figure 12-5). The methods are also reflected in a comprehensive international standard (ISO 27914:2017 - Carbon dioxide capture, transportation, and geological storage — Geological storage). The management of the risks of geological storage includes site selection, monitoring, re-planning operations, and mitigation methods. The risk level assessed for a site will always include the effect of these methods in driving down the risk level (Benson, 2007)

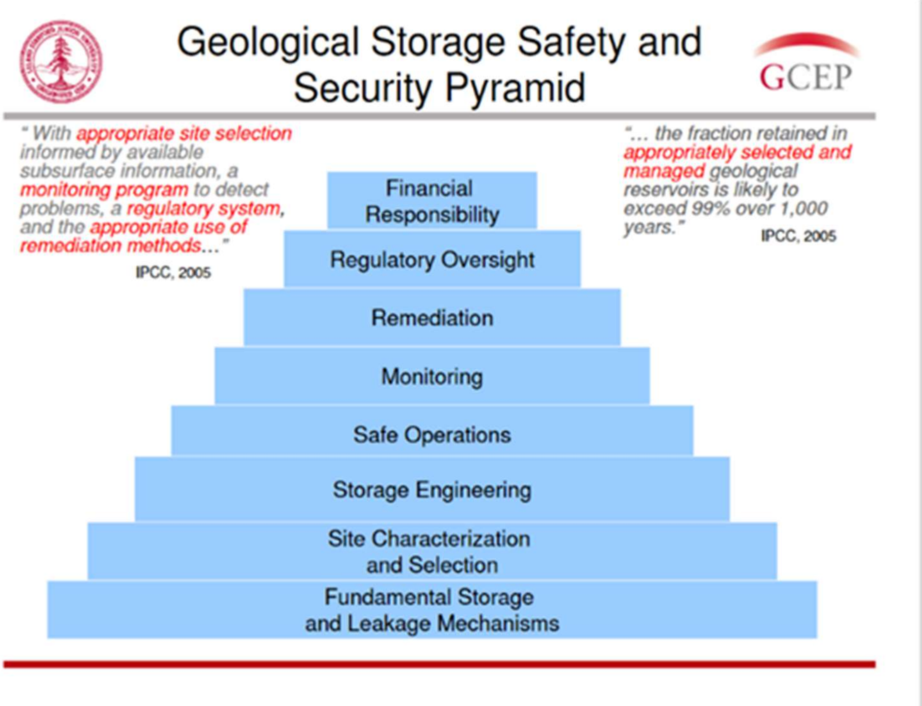



**Figure 12-5: The "safety pyramid" for geological storage, the combination of all of these steps is essential to keeping risks low (Benson, 2007)**

Regulatory conditions, such as the EU storage directive, require CO2 storage sites in the subsurface be carefully selected and designed such that "there is no significant risk of leakage" and "no significant environmental or health risks exist" (EU storage directive 2009/31/EC).

There is considerable discussion about low emission industrial hubs. Low emissions hubs are industrial centres which are designed to provide competitive, low emissions energy to encourage low emission manufacturing through shared infrastructure and circular economy principles. These hubs may include CCS along with hydrogen and manufacturing industries supported by renewable energy. The combined social and environmental impacts, risks and co-benefits of each hub and the industries it contains will be an important factor in their development. This includes onshore and offshore developments and their impact on indigenous communities, land and sea country and cultural heritage sites.

### 12.6.1 Social impacts and risks

Work published in 2019 assessed public attitudes to CCS in Australia and China. The study showed low levels of knowledge and support in both countries (Ashworth, 2019). In Australia, the perception of CCS was linked with a reluctance to support ongoing fossil fuel developments. However, there is a broad recognition in industry and government that CCS will be necessary to both enable significant cuts to atmospheric carbon and to enable a "just" transition for regions reliant on fossil energy (Partminter, 2020). Multiple modelling studies show the global need for energy is growing exponentially. Additional uptake will likely be supplied by renewables, but current infrastructure and supply and distribution chains globally will mean the rate at which dependence on fossil fuels decreases will vary significantly across countries.

Parminter and Bell (2020) co-authored the EU (European Union) funded report titled Public Perception of CCS: A Review of Public Engagement for CCS Projects. 2nd Report of the Thematic Working Group on: Policy, regulation, and public perception. In this report they note there is a lack of awareness of the role of CCS as a climate mitigation technology. Acceptance by the public and stakeholders is hampered by several factors, including the propagation of misleading beliefs (the technology does not work); lack of trust in project proponents and/or governments; fear of the environmental impacts associated with transport and storage; impact on jobs; lack of belief in climate change and objections to the use of public money for CCS. There is a public perception that the CO2 is a waste product and hence a reluctance to provide a "dumping ground" for waste produced by others.

In addition, any onshore and offshore development in Australia requires consideration of the traditional owners, the local community and other stakeholders. Although the footprint of a CCS development is small, pipelines can be required over several hundred kilometres. Consideration of impacts to culturally significant sites, heritage sites, national parks, flora and fauna are an integral part of the approvals process. Negotiation of these issues can add considerable time and cost to any onshore activity but must be considered as part of a fair and equitable transition to a low emissions future.

There are potential social benefits associated with CCS developments. These are not well quantified but are discussed in the co-benefits section. On a broader note, internationally, Australia is seen as lagging behind in its commitments to climate change, deployment of CCS as part of a portfolio of emissions reduction strategies may be seen as a positive move.

### 12.6.2 Environmental impacts and risks

CO2 leakage from geological storage is considered unlikely from properly selected sites and the potential impacts small when compared to other anthropogenic and natural stressors (Blackford et al 2020). The risk of CO2 entering the atmosphere is extremely low. Projects are designed to avoid leakage pathways and injected CO2 is comprehensively and continuously monitored. In the unlikely event of CO2 leaving the primary container, there are a number of mitigation strategies that would be immediately applied. These strategies are part of the approvals process for any CCS project.

The consequences of any $CO_2$ escaping the primary container to the environment is low as gaseous $CO_2$ dissipates very quickly in the atmosphere (IEAGHG). CO2 can accumulate under some conditions onshore, such as a prolonged absence of wind and/or in geographic depressions and can constitute a hazard. The impacts will vary for onshore vs offshore and depend on the volume release before mitigation strategies are implemented. In both cases, modelling studies have shown that a $CO_2$ plume disperses rapidly, either by wind or by currents.

Calculations that combine techno-economics and climate models have been used to set rational limits on leakage of stored $CO_2$ into the atmosphere (Haugan and Joos, 2004; Enting et al. 2008; Stone et al. 2009; Shaffer, 2010). The processes of CCS use additional energy so requiring a net climate benefit over the long-term (compared to simply venting the CO2), leads to upper limits to leakage of around 1% to 0.1% per year if there is to be a climate benefit. These limits depend on the details of the model and the time horizon for the emissions reduction benefit. Taking the smaller limit corresponds to leaking 10% of the stored CO2 over a century. The performance of geological carbon storage projects will be required to be much better than this (by orders of magnitude) to meet commercial and regulatory requirements. However, the number is useful context to quantify the net climate benefit of storage projects.

Community concerns towards CCS are often focused on issues of well integrity and groundwater contamination. Consequently, there is an enormous amount of literature on the topic of leakage associated with storage. Leakage is a broad term that includes unplanned movement of $CO_2$ to the surface and within the subsurface. In selecting a site for geological storage of $CO_2$, pathways for leakage are a key consideration. Leakage pathways from the storage reservoir to other deep layers, such as freshwater aquifers, are always assessed in detail before any final decisions to develop and inject at a site. This includes comprehensive studies to understand the geochemistry and reactions that may occur between the rocks, the water present in the rocks and the injected $CO_2$ plume. Reactions between CO2 and minerals contained in the rocks can have multiple effects, both positive and negative. For example, CO2 can react to form new solid minerals, locking up the CO2 forever (refer to Mineral Carbonation chapter), however this may also block pathways, reducing injectivity and shortening the life of the project. Alternatively, CO2 can dissolve some minerals, potentially mobilising trace elements and reducing groundwater quality. The risks associated with any impact on potable groundwater will reduce the likelihood of a project going ahead. For example, a CCS project proposed for the Surat basin in Qld undertook extensive groundwater studies and concluded that although the risk of contamination was low, the risk associated with the loss of social license made the project unviable.

Nevertheless, it is important to predict and understand potential environmental impacts and risks to human health from a range of leak scenarios in order to undertake appropriate monitoring and mitigation necessary to meet both regulatory and societal expectations (Sands et al 2022). There have been a number of studies investigating environmental impacts in natural seeps of CO2 (for example in the Victorian hot springs area), laboratory and modelling research supported by controlled release and field injection experiments. The environmental impacts are heavily dependant on the rate and nature of the CO2 expression. Controlled release experiments into the vadose zone found that there is lateral and patchy migration of CO2 in the soil profile, dependant on the soil characteristics (Ginninderra controlled release study, Geoscience Australia and CO2CRC). The soil microbial population changed and the impacts on vegetation grown at the site varied from enhanced growth to reduced growth. Natural seepage studies, such as the ones undertaken at the Daylesford natural CO2 springs in Australia, show the impacts of long-term, natural CO2 seepage from the basement. These analogue studies are useful to develop understanding of CO2 migration in the near surface and develop appropriate monitoring strategies (Roberts, et al., 2019). In addition, there have been multiple programs looking at the impacts of CO2 on groundwater quality, for example the Lawrence Berkely National Laboratory "Potential Impacts of CO2 Leakage on Groundwater Quality" (LBNL, 2007-2010). In summary, the potential environmental impacts of CO2 escaping the storage container and entering the broader environment have been well studied. The scale and impact is very site dependant and dependant on the nature and rate of the migration. It is essential that environmental impacts are investigated and quantified as part of the consideration for approval of any CCS project.

There have been a number of similar studies and programs for offshore storage. Dean et al., 2020, reviewed three controlled release projects and concluded "that the impacts of small to medium CO2 leakages from large-scale storage were assessed to be limited and localised. Integrated marine monitoring systems can detect even small leakages of 10-50 L/min at unknown locations in a large area of interest." Nevertheless, as for onshore projects, proximity to ocean resources, such as farming, must be considered and mitigation strategies proposed as a condition of approval.

Consideration of risks from legacy wells and groundwater are fundamental considerations of site characterisation, and any residual risks are mitigated by regulation. This is particularly true in Australia where there are robust regulations in place around well construction, monitoring and verification and mitigation. It is important to note that the objective of a storage project is to contain the $CO_2$. In future, loss of containment will likely pose a significant risk to the project operator, including potential loss of carbon credits associated with storage, loss of market confidence and loss of storage license.

For the transport of CO2, the $CO_2$ is dehydrated and compressed into liquid or supercritical form to minimise the risk of corrosion. There are some concerns around fugitive emissions associated with pipeline transport. However, transport via pipelines is a mature technology, for example, there are an estimated 8,000 km of $CO_2$ pipelines in the US. Pipeline construction and ongoing monitoring and maintenance are designed to minimise losses.

The surface infrastructure of an injection site is analogous in size and scale to conventional hydrocarbon production. At the simplest, it consists of a well pad and a well head connected to a short length of pipeline which quickly traverses underground, hence the surface footprint can be small.

Risks associated with injection of large volumes of fluid are increased seismicity and potential far- field pressure effects causing rising water levels. Mitigation strategies include application of threshold values for increased seismicity. Increased seismicity, above the defined threshold has been seen at CCS injection projects, for example at Tomakomai in Japan. Injection was ceased immediately, and intensive monitoring undertaken. The results concluded that the additional seismicity was within the range of normal seismicity experienced at that location. Although increased seismicity due to CO2 injection is currently assessed as low risk, understanding, and predicting fault behaviour in the presence of supercritical CO2 remains a research focus.

Comparison of CCS in the form of DACS with alternative solutions is illustrative of the relative footprints required to achieve large scale emissions reductions, Figure 12-6.

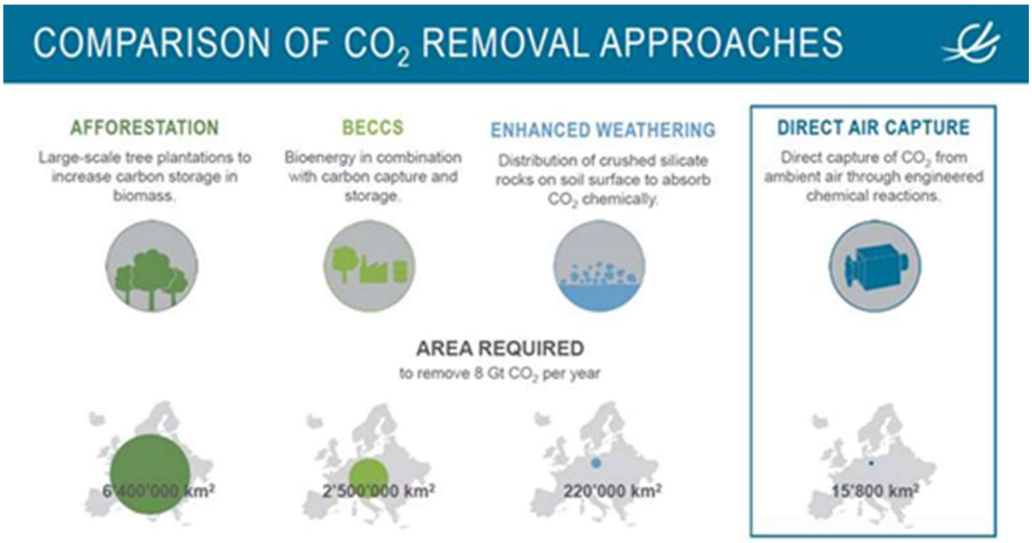



**Figure 12-6: Comparative surface footprint required for 8 Gtpa of CO2. Note that the DAC footprint is mostly associated with the DAC infrastructure. The storage infrastructure footprint is orders of magnitude smaller (Beuttler, Climeworks, CEM CCUS webinar April 2021)**

### 12.6.3 Co-benefits

It is difficult to quantify the potential co-benefits associated with geological storage, apart from the potential climate benefits. Positioning Australia as a source of clean energy and/or a sink for regional $CO_2$ emissions may have a range of socio-economic-geopolitical benefits.

Qualitatively, a CCS industry would require a range of new jobs and industries to support the activities. These would include geologists and associated experts for site characterisation, engineers, and manufacturing for construction, including wells, engineers, roads, etc.

In addition to the operational activities there would be need for ongoing monitoring and verification and regulation. One of the co-benefits observed at the Otway International Test Centre (OITC) in the Otway Basin of Victoria was the opportunity for increased local employment, during all phases of the projects. This included restaurants, hotels, hardware stores and similar.

In general, storage projects are large-scale and long-lived, so the jobs and industries generated would have longevity. The coal seam gas industry has introduced compensation mechanisms for landowners where gas developments are located. There may be similar opportunities for storage sites.

## 12.7 Barriers to implementation:

Barriers to implementation are not technological, but rather relate to social license to operate, cost and government policy. The IPCC has stated that CCS is a required technology to achieve net zero emissions. It is a part of the portfolio of solutions, all of which will likely be required.

In Australia, there is an internal conflict between our domestic and international objectives. There are several studies that suggest Australia can become almost entirely powered by renewable energy. This has led to the designation of CCS as a controversial technology, facilitating our dependence on the fossil fuel industry.

However, this doesn't address either our economic dependence on energy exports nor the hard-to-abate industries, such as iron ore processing, cement and lime. Nor does it address our role as a global citizen with responsibility for our own scope 3 emissions. As a country with abundant geological storage resources, there exists the potential to play a significant (and revenue generating) role in regional decarbonisation.

It is also interesting to note that many of the projects in the pipeline are associated with the fossil fuel industry. This industry has recognised the need to shift to low emissions energy and is actively pursuing a range of technologies to achieve this (including renewable technologies, nature-based solutions, BECCS, DACCS, etc). The scale and financial resources of the oil and gas industry, in addition to their products being the source of most $CO_2$ emissions, makes them well placed to drive the application of these technologies.

### 12.7.1 Policy and regulatory environment

The policy and regulatory environment for geological storage is still evolving in Australia. Offshore storage is possible and would be regulated under Offshore Petroleum Greenhouse Gas Storage Act (OPGGS). In 2021, the Australian Government announced five offshore areas across three basins for the 2021 Greenhouse Gas Storage Acreage release, to encourage deployment of carbon capture and storage. However, before any storage may occur, there will need to be alignment between the OPGGS and the Sea Dumping regulations, which are yet to be designed.

Australia is also a signatory to the London Convention and Protocol which seeks to promote the effective control of all sources of marine pollution, including $CO_2$. An amendment to the London protocol allows for $CO_2$ storage offshore and for transport across international boundaries. However, Australia has not ratified that amendment. To do so would require resolution of several legal, regulatory, social, techno-economic issues. These include, but are not limited to, developing standards for monitoring and verification, application and alignment with offset markets and mechanisms. Of significant importance is the long-term liability for the stored $CO_2$, which will apply for some time after the project has closed. The development of storage legislation in the USA has required a definition of the period for which this applies. The time varies from state to state. For example, the state of Wyoming will assume liability 20 years after project closure. California's CCS protocol under its Low Carbon Fuel Standard requires $CO_2$ to be securely stored for 100 years (California Air Resources Board, 2018).

Nevertheless, several neighbouring countries have expressed interest in sending $CO_2$ to Australia for storage. In addition, there is interest from industry in sending $CO_2$ separated from gas fields in the north of Australia to depleted fields in the Timor Sea. An MOU (Memorandum of Understanding) between the Timor-Leste regulator and the operator, Santos, was announced in September 2021 to progress CCS at the Bayu-Undan field in the Timor Sea (Santos, September, 2021).

Onshore regulations exist in several states, notably Queensland, South Australia, and Victoria. Western Australian regulations are being developed. The Gorgon Project, which sits on Barrow Island, is regulated under the Barrow Island Act which specifically and only applies to Barrow Island. The previously mentioned Santos Moomba project will be the first. There are no projects actively testing the application of these regulations. While not a barrier, there is a degree of uncertainty associated with the implementation of these new regulations. The Otway International Test Centre (OITC) operates under an exemption for scientific research.

### 12.7.2 Social licence and stakeholder acceptance

Social license and stakeholder acceptance are tangible risks for geological storage. The general understanding of geology and subsurface processes is low among the public and other stakeholders. There is a view that CCS enables the fossil fuel industry and hence is prolonging the life of the fossil fuel industry. Further, there is strong but incorrect, media representation that the technology doesn't work or is unsafe. Although this is countered by numerous IPCC (Intergovernmental Panel on Climate Change) reports, which state hard-to-abate industries, such as the construction industry will need some form of $CO_2$ sequestration, including CCS.

For Australia, this is further countered by our economic dependence of energy export. Australia is one the largest exporters of LNG globally. Hence, there is a growing imperative for Australia to account for the Scope 3 emissions associated with these exports. Although there are strong indicators of a transition to a hydrogen economy, the timing is unclear. Several countries (Japan, Korea) are planning to transition to hydrogen before the technology for renewable hydrogen is predicted to become economic at scale, so are looking for the more conventional sources of hydrogen production, coupled with CCS.

### 12.7.3 Technology performance variability

The technical performance of a specific storage site is controlled by the geology present at the site. The performance of the surface infrastructure is controlled by engineering technology. This technology is imported from the oil and gas industry and is very mature. Some of the key variability associated with the surface infrastructure will relate to the risk of corrosion associated with the presence of any wet $CO_2$ and any fugitive emissions produced during normal well operations.

The geological performance is dependent on the nature and properties of the rocks where the $CO_2$ is stored and sealed.

### 12.7.4 Financial proposition and costs and access to capital

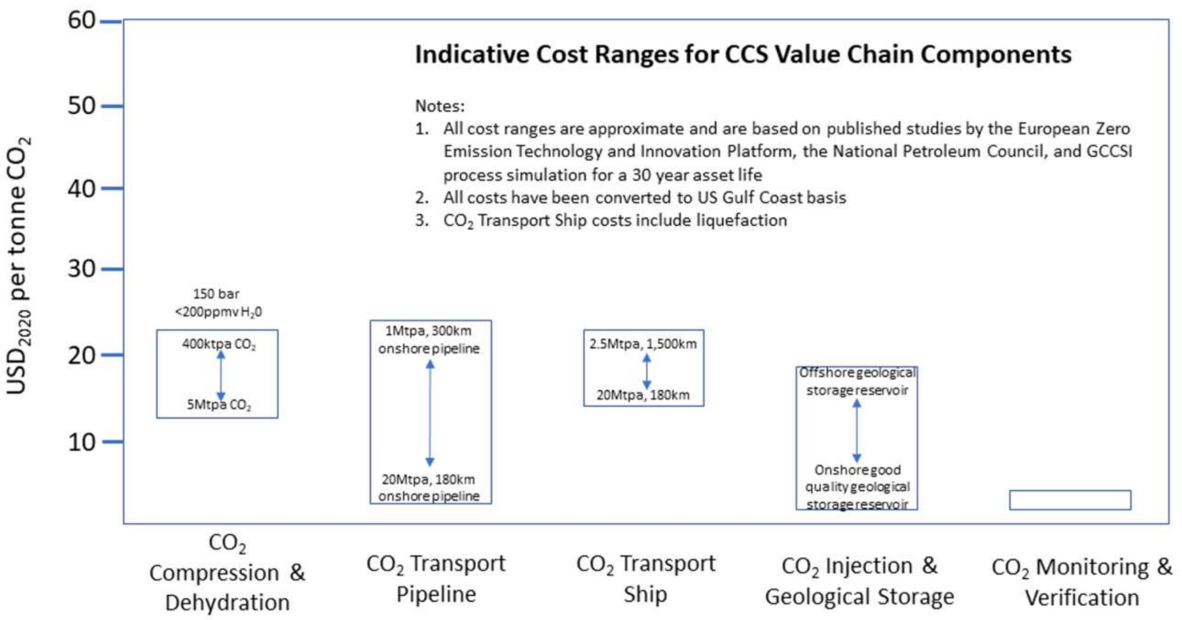
CCS has long been considered as “too expensive.” Capturing $CO_2$ from stationary sources, such as coal fired power stations, is a capital intensive cost. The cost of storage is highly dependent on the distance between the source of the CO2 emissions and the location where the $CO_2$ will be stored (the “sink”). The costs of each component of the value chain vary with the greatest range shown for transport and for the injection and storage component (including characterisation). Transport costs can be reduced by reducing the distance between source and sink. Geological storage costs will vary depending on the type of storage (saline aquifer vs depleted reservoir), the amount of characterisation and/or remediation required, and the transport distance, Figure 12-8a. Cost estimates for the transport and storage process vary from a little as $5-$14per tonne $CO_2$ up to $790 per tonne $CO_2$, however, these estimates are from 2015, Figure 12-8b (APGT, 2015).

New business models are being explored to offset the costs of CCS and to generate revenue by providing a storage service for emitters. For example, the “hub” concept where multiple emitters (small and large) can access transport and storage infrastructure. The most well known and most developed example of this hub concept is the Norwegian Northern Lights Project. There are several hub concepts being explored globally, including for Australia, in the Northern Territory and in Western Australia. Many different countries are exploring public-private partnerships to develop these transport and storage (T&S) networks. The UK has the Carbon Capture and Storage Infrastructure Fund (the CIF) which forms part of the governments wider Ten Point Plan (CIF Doc).

The highest risk associated with CCS is not the risk of the $CO_2$ escaping to the surface, it is the economic risk that once investment occurs, the geological container is too small to contain the amount of $CO_2$ required for storage, or conversely, that the available source of $CO_2$ is insufficient to justify the capital expenditure. The risk of $CO_2$ escaping the primary container is very low as the project is designed to prevent such events and the likelihood that $CO_2$ would reach the surface is extremely limited. In the case of any losses, there is an additional risk to the project proponents associated with the cost of implementing mitigation strategies and accounting for the lost carbon credits.

A recent study by the GCCSI provides indicative cost ranges for the storage component of the CCS value chain (GCCSI, 2021), based on US Gulf Coast data and the references in the caption.

The nearest published equivalent for Australia is the Australia Power Generation Technology report from 2015. It shows that the relative cost of storage varies significantly with distance from sink. The report makes a number of assumptions about costs, including the cost of electricity, which are likely out of date. Hence, the absolute numbers should be used with caution. The report also discusses the cost efficiencies associated with multiple users accessing a single sink. The CER CCS Methodology is predicated on this assumption, allowing for additional users to enter or leave the storage facility.




[7] Based on GCCSI process simulation and analysis of: ZEP 2019, The cost of subsurface storage of $CO_2$, ZEP Memorandum, December 2019. IEAGHG ZEP 2011, The Costs of $CO_2$ Storage, Post-demonstration CCS in the EU. National Petroleum Council 2019, Meeting the Dual Challenge, A Roadmap to at-scale deployment of carbon capture use and storage. National Petroleum Council 2019, Topic paper #1, Supply and Demand Analysis for Capture and Storage of Anthropogenic Carbon Dioxide in the Central US.

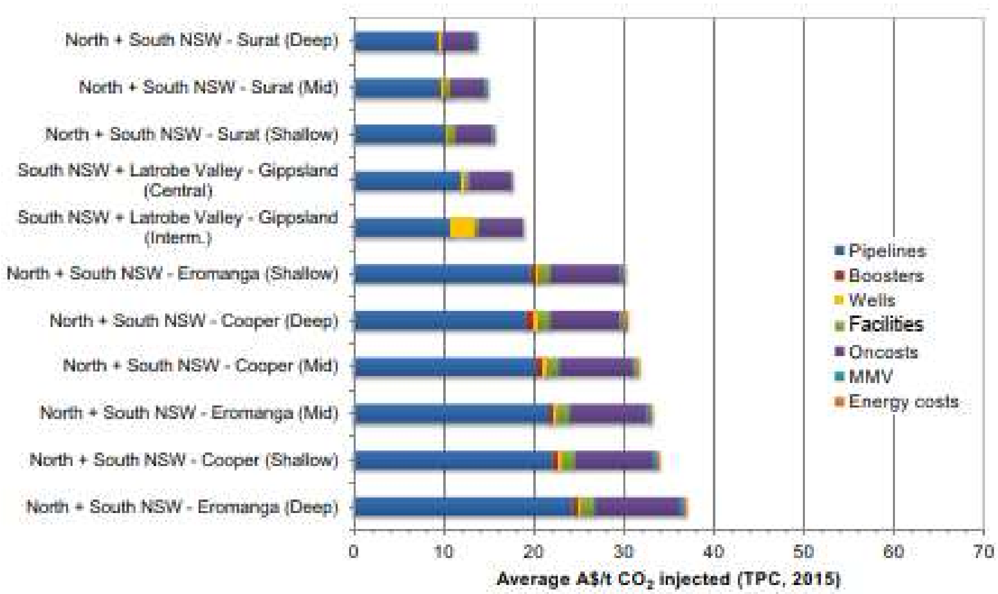



**Figure 12-4: Indicative cost ranges for the CCS Value Chain Components and Average cost per tonne injected – both figures taken from the APGT report, 2015. Figure 139, average total plant cost over 30 years for multiple source to single sink cases.**

Quest carbon capture and storage facility in Canada has captured and safely stored 4 million tonnes of carbon dioxide over four years, approximately 1Mtpa, the equivalent annual emissions of about one million cars. The project captures CO2 from the manufacture of hydrogen for upgrading bitumen into synthetic crude oil. The CO2 is transported by a 65-kilometre pipeline and stored more than two kilometres underground below in dedicated rock formations. Quest is the first large-scale CCS project in North America to store CO2 exclusively in a deep saline formation, and the first to do so globally since the Snøhvit CO2 Storage Project became operational in Norway in 2008. Shell estimates that a similar project would cost 20 to 30 per cent less given the learnings at Quest (GCCSI, 2019)

## 12.7.5 Industry supply chains and skills

The development of a CCS industry provides an opportunity to pivot expertise and skills from the oil and gas industry as the technologies and skills are highly similar to hydrocarbon exploration and production practices in many ways. The storage technology is derived from the oil and gas industry, hence the reservoir engineers, surface engineers, geologists etc are well placed to apply skills to the CCS industry. In many ways it is the reverse of the oil and gas industry. Similarly, the application of engineering skills and expertise to the capture and transport industries will require new jobs and industries to support these activities.

The supply chains are like those of the oil and gas industry as the infrastructure needs are similar. Market opportunities or market creation

There is increasing need for each country and industry to account for its emissions. Australia is highly dependent on exporting energy, currently in the form of coal and gas. The projected demand for these products varies considerably. Many countries are legislating or proposing reduced emission targets by 2050. The pathways to realisation of these targets is less clear. It will also vary significantly for different countries. Australia may be able to supply our own energy requirements, many other countries will not. For Australia to maintain its economic position, there will be a need to develop low or zero emissions energy exports at a cost and rate that is competitive with other low or zero emissions energy producers.

Therefore, there is an imperative to move rapidly to low emissions energy.

## 12.8 Scaling knowledge gaps:

There are very few technological barriers to deployment of CCS. The major barriers are cost and the perceived delay of the transition away from fossil fuels

1. How to reduce time taken to characterise a potential site?
    a. The technology challenges are associated with reducing cost by optimising the storage capacity and reducing time taken to characterise a site to a sufficient confidence level. The concept of "Learning By Doing" demonstrates that the more frequently an activity is undertaken, the more efficient it will become. The same applies to CCS and other sequestration technologies.
2. What are best business models for reducing risk for large capital investments required?
    a. Successful development of a CCS industry will require innovative business models and likely public-private partnerships to optimise infrastructure and fund capital intensive projects, such as those being developed in Norway and the UK.
3. How to reduce costs and optimisation of monitoring and verification technologies and programs.
4. How to reduce costs, development time and optimisation of site selection and characterisation.

## 12.9 Chapter References


Ashworth, P., Sun, Y., Ferguson, M., Witt, K., She, S., 2019, Comparing how the public perceive CCS across Australia and China, International Journal of Greenhouse Gas Control, Volume 86, Pages 125-133, ISSN 1750-5836

Australian Power Generation Technology APGT 2015, copyright Electric Power Research Institute

Ball, J., 2022. The Big Business of Burying Carbon | WIRED; online article July 28

Benson*, S.M., 2007. Presentation given at the WRI CCS Long-Term Liability Workshop Washington DC June 5, 2007. http://pdf.wri.org/sally_benson_ccs_june5.pdf

Blackford, J., Alendal, G., Avlesen, H., Brereton, A., Cazenave, P.W., Chen, B., Dewar, M., Holt, J. and Phelps, J., 2020. Impact and detectability of hypothetical CCS offshore seep scenarios as an aid to storage assurance and risk assessment. International Journal of Greenhouse Gas Control, 95, p.102949.

Bradshaw,B.E., Spencer, L,K., Lahtinen, A., Khider,K., Ryan, D., Colwell, J.B., Chirinos, A., Bradshaw, J., Draper, J.J., Hodgkinson, J., McKillop, M., 2011, An assessment of Queensland's CO2 geological storage prospectivity — The Queensland CO2 Geological Storage Atlas, Energy Procedia, Volume 4, Pages 4583-4590, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2011.02.417.

California Air Resources Board, 2018, Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard, 139 pp

Carbon Storage Taskforce 2009, National Carbon Mapping and Infrastructure Plan – Australia: Full Report, Department of Resources, Energy and Tourism, Canberra

Dean, M., Blackford., Connelly, D., Hines, R.,2020, Insights and guidance for offshore CO2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects, International Journal of Greenhouse Gas Control, Volume 100, ISSN 1750-5836.

Department for Business, Energy & Industrial Strategy, The Carbon Capture and Storage Infrastructure Fund, An update on the Design of the CCS Infrastructure Fund, May 2021, https://www.gov.uk/government/publications/design-of-the-carbon-capture-and-storage-ccs-infrastructure-fund

GCCSI, 2019, Quest carbon capture and storage facility in Canada reaches new milestone - Global CCS Institute

GCCSI, Global Status of CCS 2021, CCS Accelerating to net zero, pp 43.

IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

Kearns, D., Liu, H., Consoli, C., 2021, Technology Readiness and Costs of CCS. GCCSI, 50 pp.

LBNL 2007-2010, Potential Impacts of CO2 Leakage on Groundwater Quality, https://eesa.lbl.gov/projects/potential-impacts-of-co2-leakage-on-groundwater-quality/

Logan Brunner, Filip Neele, 2017, MiReCOL – A Handbook and Web Tool of Remediation and Corrective Actions for CO2 Storage Sites, Energy Procedia, Volume 114, 4203-4213, ISSN 1876-6102.

LETS, 2021, LOW EMISSIONS TECHNOLOGY STATEMENT 2021 Australian Government Department of Industry, Science, Energy and Resources

N. Kampman, et al. "Observational evidence confirms modelling of the long-term integrity of CO2-reservoir caprocks" Nature Communications 28 July 2016.

Parmiter, P., Bell, R., 2020, CCUS Projects Network, Public Perception of CCS: A Review of Public Engagement for CCS Projects. 2nd Report of the Thematic Working Group on: Policy, regulation and public perception, EU CCUS Projects Network (No. ENER/C2/2017-65/S12.793333), financed by the European Commission

Roberts, J., Leplastrier, A., Feitz, A., Shipton, Z., Bell, A., Karolyte, R., 2019, Structural controls on the location and distribution of CO2 emission at a natural CO2 spring in Daylesford, Australia, International Journal of Greenhouse Gas Control, Volume 84, 36-46, ISSN 1750-5836.

Sands, C., Connelly, D.P. and Blackford, J.C., 2021. Introduction to the STEMM-CCS special issue. International Journal of Greenhouse Gas Control, 113, p.103553.

Santos, November, 2021, Santos announces FID (Final Investment Decision) on Moomba carbon capture and storage project | Santos

Santos, September, 2021, https://www.santos.com/news/mou-signed-on-bayu-undan-carbon-capture-and-storage/).

Tcvetkov, P., Cherepovitsyn, A., Fedoseev, S., 2019, Public perception of carbon capture and storage: A state-of-the-art overview, J. Heliyon, Elsevier, https://doi.org/10.1016/j.heliyon.2019.e02845

Whittaker, S., and Perkins, E., 2013, Technical aspects of Co2 enhanced oil recovery and associated carbon storage, Global Carbon Capture and Storage Institute (GCCSI), 14pp

# 13 Bioenergy with Carbon Capture and Storage

| | | |
|---|---|---|
| Emission Type | Avoided | Negative |
| Enabling Capture Technology | Biological | Engineered |
| Enabling Storage Technology | Biological | Engineered |

**Figure 13-1: BECCS technology type**

## 13.1 Summary

Bioenergy with carbon capture and storage (BECCS) is a two-step emissions removal technology. Organic matter (biomass) is converted to energy in the first step. In the second step, $CO_2$ released in that conversion is captured, compressed into liquid and stored underground in geological formations. This section will focus on the first step.

There are three main BECCS pathways: producing heat and electricity through combustion; producing biofuels through gasification or fermentation; and producing hydrogen through gasification, pyrolysis or fermentation. These pathways differ in regarding which feedstock, energy conversion process and $CO_2$ capture and storage (CCS) technology is used.

Globally, installed BECCS capacity ranges from 1 to 1.5 $MtCO_2$ per year (Consoli, 2019; Fajardy, 2020). Australia currently has no operating BECCS projects but does have been extensive experience in the use of biomass for producing energy. In 2021, Australia had more than 100 bioenergy plants, generating over 3,000 GWh of electricity. In addition, it has several current CCS projects. For example, Chevron Corporation's Gorgon project in Western Australia is the world's largest CCS project, geologically storing 3–4 $MtCO_2$ per year for the next 30–40 years.

**Sequestration potential**

Global potential estimates for $CO_2$ removal through BECCS range from 1.2–12 GtCO-e per year. Economic sequestration is estimated to be ~181Mt per year based on biomass estimates from Crawford et al, 2016. Factors restricting its potential include availability of biomass, BECCS plant capacity and availability of geological storage.

Current energy production from biomass accounts for 47% of Australia's renewable energy production and 3% of total energy consumption (DISER, 2021b). Modelling has suggested that Australia could remove a total of 25–38$MtCO_2$-e per year by 2050, offsetting up to 15% of the 253 Mt of gross emissions from sectors including energy, agriculture and transport (DISER 2021b, Pour et al 2018) at a cost of $100 per tonne.

**Technological and commercial readiness**

The individual components of BECCS technology (converting biomass into energy; capturing, transporting and storing $CO_2$), are all mature; however, the combination of technologies has struggled to be widely applied due to uncertain policy support and economic feasibility.

There are 27 commercially operating CCS facilities worldwide, with a capture capacity of 36.6 $MtCO_2$ per year, but few combine this with bioenergy technologies. The five existing commercial BECCS facilities are all located in North America, and all combine CCS with bioethanol production.

Both bioenergy and CCS technologies allow scalability. However, BECCS scalability is challenged by biomass supply, geological storage capacity, upscaling costs, competition for other land, water, and fertiliser uses, and rising concerns about sustainability.

The $CO_2$ removed from the atmosphere through BECCS is geologically stored and this is unlikely to be reversed. Leakage of $CO_2$ could pose a threat to long-term storage of injected $CO_2$, but it is not widely accepted as a major risk. In areas where well densities are moderate and storage is regulated, over 98% of injected $CO_2$ can be securely retained underground for millions of years.

**Social and environmental risks and co-benefits**

While BECCS can increase and diversify rural incomes, it can also eliminate small-scale farmers or expose them to global market fluctuations. Large-scale deployment of BECCS could create land competition and increase food prices. As an effective and convenient solution to limit global warming to 1.5 °C, BECCS may lead countries to over rely on future 'negative emissions' while not taking urgent actions to reduce emissions today.

Negative environmental impacts have been identified as a major limitation for the use of BECCS. A commitment to deploying large-scale BECCS requires vast amounts of high-quality land and water for growing and processing bioenergy feedstock. Using algae or lignocellulosic biomass can alleviate pressure on land use, but still require intensive use of water and nutrients.

**Barriers to implementation**

A major barrier to BECCS investment and deployment is the lack of strong policy incentives and a stable regulatory environment. Policymakers could mitigate the risk of BECCS investment by providing subsides, tax credits for geological $CO_2$ sequestration, and price guarantee mechanisms. Setting BECCS as a high political priority would also help eliminate public concerns around the negative environmental impacts of the technology and influence stakeholder acceptance. Other barriers to implementation include substantial upfront costs, industry supply chain and skills issues, and current market conditions.

**Scaling knowledge gaps**

To realise the potential deployment of BECCS in Australia, the following research questions need to be addressed.

1. What is the technology's maximum potential for $CO_2$ removal?
2. What are suitable deployment patterns and scaling pathways to maximise $CO_2$ removal and energy production and minimise costs and ecological impacts?
3. What are the appropriate policy incentives to encourage the technology?

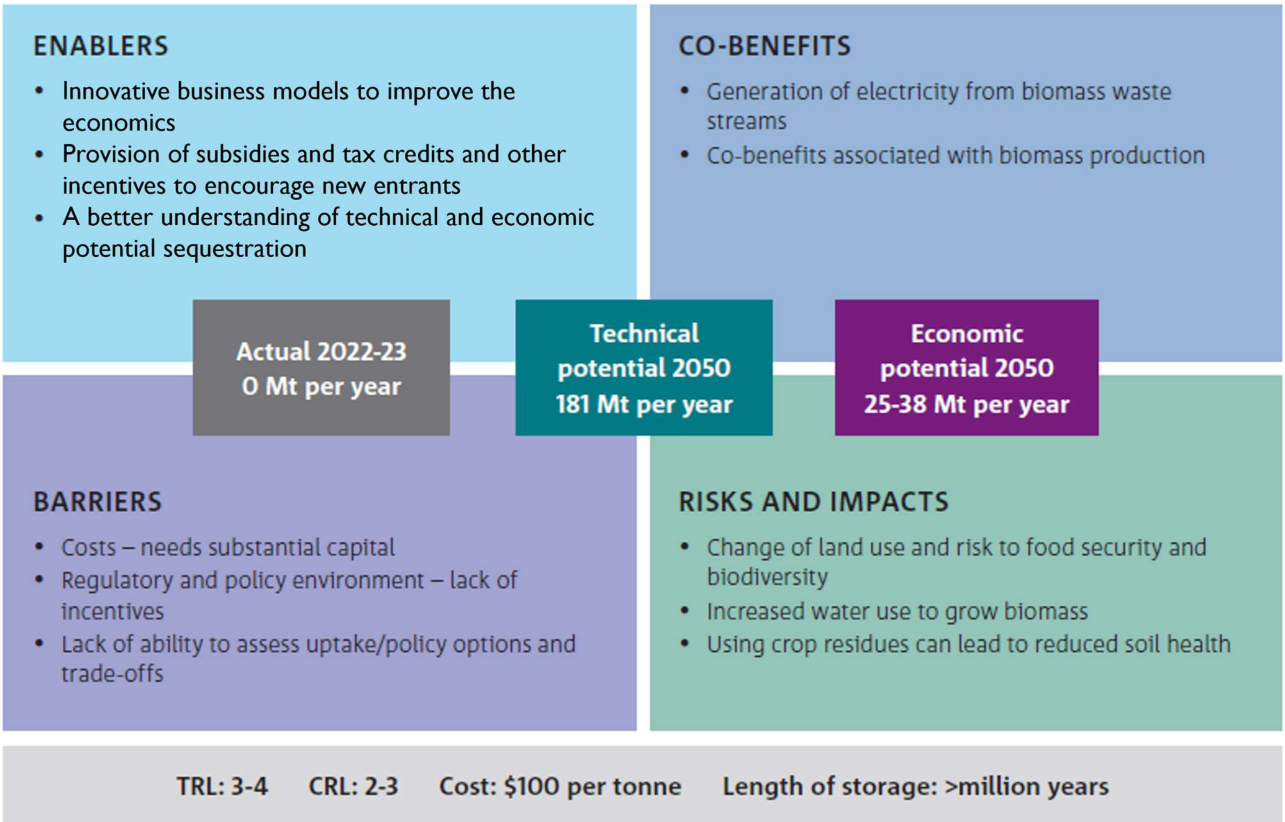



**Figure 13-2: Summary of BECCS technology**

## 13.2 Description and current uptake

Bioenergy with carbon capture and storage (BECCS) is a carbon removal technology that mainly involves two steps: (1) converting biomass (organic material) into energy and (2) capturing carbon emissions released from the conversion process and storing them into geological formations (Williamson, 2016). Bioenergy generation is considered as carbon neutral because the released carbon dioxide (CO2) when converting biomass to energy was first sequestered from the atmosphere through photosynthesis during the growth of biomass. BECCS is therefore a negative emissions technology as the released CO2 is captured and compressed into liquid for underground storage. A full treatment of the geological storage process is found in section 12.

A variety of biomass feedstocks are used to produce energy. They are typically grouped into four categories: dedicated energy crops, agricultural residues, forestry by products/residues, as well as industrial and municipal wastes. The conversion routes of a biomass feedstock to energy fall under two primary categories: thermochemical (e.g., gasification, combustion, pyrolysis, and liquefaction) and biological (e.g., biophotolysis, water-gas shift reaction, and fermentation) (Ni et al., 2006). Energy can be extracted in a variety of forms, such as heat, electricity, biofuels, and hydrogen. There are mainly three types of technologies for $CO_2$ capture: pre-combustion, post-combustion, and oxy-fuel combustion (Kanniche et al., 2010).

Considering feasibility of combining different biomass feedstocks, conversion routes, and energy forms, BECCS technologies fall in three pathways (Fajardy, 2020), as shown in Figure 13-3; (1) producing electricity through combustion (in circulating pulverise bed plants, chemical looping combustion plants, pulverised combustion plants, and combined heat and power plants to produce both electricity and heat) or through gasification (in an integrated combined cycle), (2) producing biofuels through gasification and Fischer-Tropsch conversion or fermentation, and (3) producing hydrogen through gasification, pyrolysis, or fermentation. In the pathways implemented through combustion, an oxy-fuel combustion system and a post-combustion system can be applied to capture $CO_2$ when combustion occurs in oxygen and in air, respectively. A pre-combustion system can be applied in the gasification pathways to capture $CO_2$ from the syngas. Via biomass fermentation, a portion of $CO_2$ is released as high purity $CO_2$ and can be directly captured.

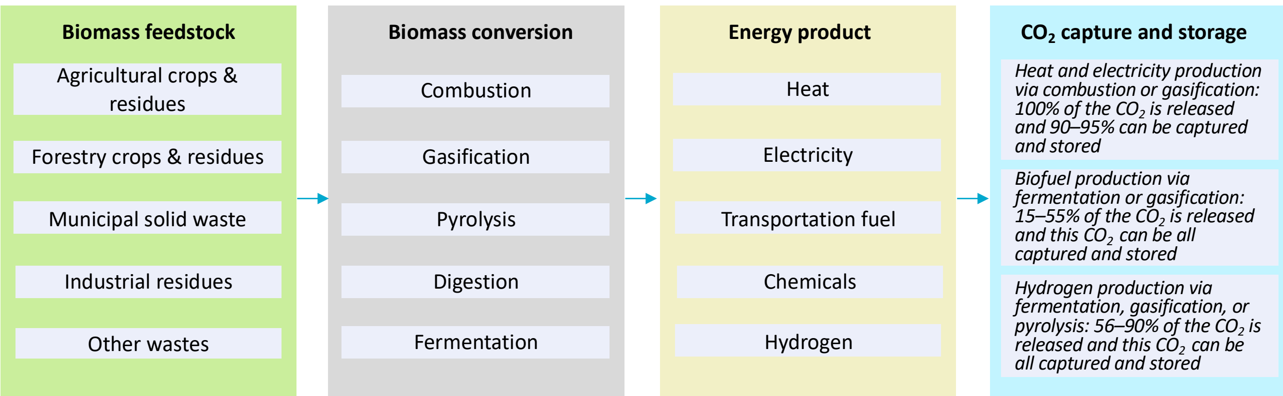



**Figure 13-3: Illustration of different BECCS pathways.**

Globally, the installed BECCS $CO_2$ removal capacity has been approximately 1–1.5 $MtCO_2$ per year, mostly in North America and Europe (Consoli, 2019; Fajardy, 2020; Pour, 2018). Although there are no operating BECCS projects in Australia, BECCS is technically viable. There has been extensive experience in the use of biomass for producing energy, involving co-firing with coal. In 2021, Australia had over 100 bioenergy plants, generating 3,187 GWh of electricity (1.4 % of the nation's total electricity generation) (Clean Energy

Council, 2022). There have been several CCS projects currently available in Australia see section 12.3. For example, the Gorgon project operated by Chevron Corporation is the world's largest $CO_2$ storage project in Western Australia, geologically storing 3–4 Mt $CO_2$ per year for next 30–40 years (Pour et al., 2018).

There are some concerns that the potential for BECCS to realise the global estimates of sequestration has been overstated (Galik, 2020). IPCC (IPCC. Special Report on Global Warming, 2018) has therefore indicated perhaps a reduced dependence on BECCS is prudent, again strengthening the argument for a portfolio of approaches for sequestration.

**Case study:** Decatur project

The BECCS plant/facility owned by the agribusiness firm Archer Daniels Midland at Decatur in Illinois, United States, is the only BECCS project that is operating at the commercial scale in the world at present (Consoli, 2019). The plant produces ethanol (largely for use in road transportation) from corns based on the fermentation process and generates high purity CO2 in the process. The CO2 is directly captured, compressed, dehydrated, transported through a 1.9-km pipeline, and injected into local porous sandstone formations in the Illinois Basin. Since 2017, the plant has had the capacity of capturing approximately 1 Mt of carbon dioxide per year.

## 13.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt.yr $^{-1}$) | Key evidence |
|---|---|---|
| **Technical Potential** | Global: 1,200–12,000<br>Australia: 180.6 | Based on (UTAS et al., 2019)<br>See section 13.3.1 for estimation details |
| **Economic potential by 2025** | Unknown | |
| **Economic potential by 2035** | Unknown | |
| **Economic potential by 2050** | Australia: 25<br>Australia: 38 | Based on Pour et al. (2018)<br>Based on (DISER, 2021a) |

Table 13-1: Summary of BECCS sequestration

### 13.3.1 Technical sequestration

The global potential estimates for BECCS' carbon dioxide removal range from 1.2–12 GtCO2 per year (UTAS et al., 2019). There has been little research on estimating the potential for BECCS in Australia. The fundamental factors that restrict BECCS sequestration potential are (1) availability of biomass (and land and water for growing biomass), (2) capacity of BECCS plants to process the biomass and capture the released CO2, and (3) availability of geological storage where the released CO2 can be injected and stored.

Current energy production from biomass accounts for 47% of Australia's renewable energy production and 3% of total energy consumption (DISER, 2021b). Modelling for Australia's bioenergy roadmap suggests that available biomass can support bioenergy production up to 20% of Australia's total energy consumption by 2050 (ENEA and Deloitte, 2021). Crawford et al. (2016) provided spatial estimates of potential available biomass for Australia's bioenergy. The potentially available biomass was estimated at 114 Mt year$^{-1}$ in 2050, with 29.3 Mt of short rotation trees, 27.7 Mt of crop stubble, 19.7 Mt of grasses, 12.8 Mt of plantation forests, 10.9 Mt organic waste, 7.9 Mt of native forests, and 5.5 Mt of bagasse per year. We assume that 100% of carbon dioxide removed by the biomass from the atmosphere through photosynthesis during its growth is released during biomass combustion, and 90% of the released carbon dioxide can be captured and stored. The technical sequestration can be estimated at 180.6 Mt per year using

$$CD_i = B_i \cdot cc_i \cdot \frac{MW^{CO_2}}{MW^{C}} \cdot 90\%$$

where $CD_i$ is the stored carbon dioxide from biomass feedstock $i$ and $cc_i$ is the carbon content of biomass feedstock $i$ (parameters from $cc_i$ are from Fajardy (2020)).

As one of the fundamental limiting factors, the storage potential of $CO_2$ is not considered as the bottleneck for BECCS sequestration potential in Australia, although regional or local storage capacities and reliability may vary substantially. Storage potential for Australia is discussed in section 12.2.

No work has been done to assess the maximum biomass that can be produced for BECCS in Australia.

### 13.3.2 Economic sequestration

An assessment by Pour et al. (2018) suggested that through BECCS, Australia could deliver a total of 25Mt of $CO_2$ per year by 2050 (medium confidence). This assessment applied a multiplier of 25% into the available biomass (5 Mt of bagasse, 9.46 Mt of landfill gas, 3.94 Mt of municipal solid waste, and 8.8 Mt of forest residue) estimated by Clean Energy Council (2008) as sustainable biomass inputs to their BECCS models for calculating negative $CO_2$ emission potential.

In Australia's long-term emissions reduction modelling report (DISER, 2021a), BECCS is used to remove 38Mt of $CO_2$ in 2050 in the proposed technology plan (higher levels of BECCS in other scenarios, low confidence), offsetting 15% of the 253Mt of gross emissions from sectors including energy, agriculture, and transport. However, it is unclear where the biomass for BECCS would be sourced and how the negative emissions from BECCS were calculated.

## 13.4 Technology Readiness Potential and Commercial Readiness

### 13.4.1 Technology Readiness

| Technology Readiness | \$/t CO2e | Key Evidence |
|---|---|---|
| **TRL 2–TRL 9 depending on which biomass feedstock, conversion route, energy form, and CCS technology is selected** | \$70–\$80/t CO2e (2017 USD) (Pour et al., 2018) | Globally installed BECCS $CO_2$ removal capacity has been approximately 1–1.5 Mt$CO_2$ per year (Consoli, 2019; Fajardy, 2020)<br>Archer Daniels Midland (an American agribusiness firm) operates a large-scale commercial BECCS facility in Decatur, Illinois, producing bioethanol from corns and capturing up to 1 Mt of $CO_2$ released from the formation process per year, and storing the $CO_2$ in a geological storage site underneath the facility (Fajardy, 2020) |

| | |
|---|---|
| | Four small-scale BECCS facilities are currently operational, producing ethanol and using $CO_2$ for enhanced oil recovery (Consoli, 2019) |

Table 13-2: Technology readiness assessment for BECCS

The individual technology components that form the BECCS technology, such as converting biomass into energy as well as capturing, transporting, and storing carbon emissions released from the conversion process, are all mature. Technical readiness levels for using lignocellulose (TRL 9), agricultural residues (TRL 9), organic waste (TRL 9), and algae (TRL 8) as bioenergy feedstock range from TRL 8 to TRL 9 (Consoli, 2019). Different conversion technologies from biomass to energy, such as combustion (TRL 9), gasification (TRL 2 – TRL 8), pyrolysis (TRL 7 – TRL 9), or fermentation (TRL 6 – TRL 9), range from TRL 2 to TRL 9 (Consoli, 2019). Carbon capture and storage (CCS) technology is also mature; however, the technology has mostly struggled to be widely applied due to uncertain policy support and economic feasibility. Although further combination of the bioenergy technology and CCS technology adds complexity and raises a number of issues regarding large-scale deployment of BECCS (Bellamy et al., 2019), there are no technological barriers to BECCS deployment as no additional technology is needed.

The cost of negative carbon achieved through BECCS technology varies largely. A recent review of the entire literature (Fuss et al., 2018) found the cost ranged from US$15–400/t$CO_2$. An Australian study estimated the cost of negative carbon as US$70–$80/t CO2e (Pour et al., 2018).

As the third-generation bioenergy feedstock, algae biomass is regarded as a promising BECCS feedstock without competing with food production (Choi et al., 2019). Compared with terrestrial plants, algae have shorter harvesting period due to its high photosynthetic efficiency and growth rate. It can grow with poor-quality water and non-fertile land. Over the past few decades, a large number of studies have been conducted to commercialise algal biofuels and animal feeds (Beal et al., 2018). However, very limited biomass products are available in the market, and commercial BECCS based on algae is still at pilot scale. Large-scale algae production is challenged by its high production cost and the suitability of locations (to source inexpensive water, carbon dioxide, and energy) for high productivity (Beal et al., 2018; Choi et al., 2019).

## 13.4.2 Commercial Readiness

| Commercial Readiness | Key Evidence |
|---|---|
| **CRI 2-3** | The five existing BECCS facilities (Illinois Industrial CCS, Kansas Arkalon, Bonanza CCS, Husky Energy $CO_2$ injection, and Farnsworth) are ethanol production plants with CCS, with approximately 1.5 million tonnes capture capacity per year. |

Table 13-3: Commercial readiness assessment for BECCS

Bioenergy and biofuels technologies have been commercially used. Currently there are 27 commercially operational CCS facilities around the world, with 36.6 Mt $CO_2$ capture capacity per year (Global CCS Institute, 2021). Efforts to combine the bioenergy and CCS technologies are limited. At present, the largest and most commercially attractive BECCS application is the combination of bioethanol and CCS. The five existing BECCS facilities (Illinois Industrial CCS, Kansas Arkalon, Bonanza CCS, Husky Energy $CO_2$ injection, and Farnsworth) are ethanol production plants with CCS (Consoli, 2019).

## 13.5 Scalability, Length of storage, Measurement and Verification

### 13.5.1 Scalability

BECCS is technically viable and scalable. Both bioenergy and CCS technologies allow scalability (Almena et al., 2022), and many studies suggested that keeping warming below 1.5 degree needs large-scale deployment of BECCS (e.g., Minx et al., 2018). However, there are rising concerns about the sustainable scalability of the BECCS technology (Rogelj et al., 2016): large-scale deployment of BECCS is untested and could prove controversial due to its potential social and environmental impacts (see sections 13.6.1 and 13.6.2). In addition, its scalability in the real world is restricted by available biomass supply, geological $CO_2$ storage capacity, feasible costs, competition for other land, water, and fertiliser uses (Fridahl and Lehtveer, 2018). Upscaling cost varies according to the above restricting factors. Low cost appears in upscaling BECCS facilities with abundant biomass and short distances to $CO_2$ storage sites (Fuss et al., 2018).

### 13.5.2 Length of Storage.

Among negative emissions technology (NET) options, BECCS is not likely to be reversed as the CO2 removed from the atmosphere is geologically stored through BECCS. For more detail see geological storage in section 12.5.2.

## 13.6 Social, environmental impacts, risks and co-benefits

### 13.6.1 Social impacts and risks

The deployment of BECCS can increase and diversify rural incomes, but it also can eliminate small-scale farmers or expose them to fluctuations of world markets (Buck, 2016). Large-scale deployment of BECCS will create competition for land and further lead to the rise of food prices. This impact is relatively local – at the level of farmer, compared to broader impacts, e.g., food cost increase affects wider society. Social impacts and risks associated with CCS are discussed in section 12.6.

### 13.6.2 Environmental impacts and risks

Negative impacts of BECCS on environment have been identified as major limitations for its large-scale deployment. Large-scale deployment of BECCS, which is required in many scenario analyses to limit global warming to 1.5°C, could lead to a great need for land, water, and nutrients (Bonsch et al., 2016; Heck et al., 2018; Smith et al., 2016). A global net removal of 3.3 Gt carbon dioxide per year from the atmosphere in 2100 requires 380–700 Mha land and 720 $km^3$ $yr^{-1}$ water (Smith et al., 2016). A commitment to deploying large-scale BECCS requires vast high-quality land for growing bioenergy crops and this could be possible through deforestation and/or create competition for land use with food production. While food producers need to find other land for food production, which may lead to further deforestation. Meanwhile, food prices may increase due to impacted food production. In addition, as forests are converted to agricultural land for producing energy and food, warming could be accelerated.

Agricultural intensification can mitigate the negative impact but lead to biodiversity loss and increased biochemical flows. Using crop residues as biomass feedstock may cause soil depletion and erosion. Limiting BECCS deployment to marginal land can result in detrimental impacts on biodiversity. Using algae or lignocellulosic biomass can alleviate pressure on land use, but still requires intensive use of water and nutrient. The negative impacts of BECCS deployment include intensive use of water for biomass growth, water pollution caused by fertiliser application, and water consumption in the BECCS power plant.

In Australia, agriculture currently accounts for 55% of land use and 24% of water extraction (ABARES, 2022). Rainfall in Australian agricultural regions is projected to decrease with prolonged drought and reduced soil moisture (Whetton and Chiew, 2021). Therefore, feasibility assessment of large-scale deploying BECCS in resource-constrained Australian land system needs to consider costs and benefits of competitive land uses via comprehensive, integrated, national scale analyses at spatial, temporal, and sectoral resolution (Gao and Bryan, 2017).

Environmental impacts and risks associated with CCS are discussed in section 12.6.2.

### 13.6.3 Co-benefits

A major co-benefit from BECCS is that it produces energy (such as heat, electricity, biofuels, and hydrogen) while other negative emission technologies (NETs), such as direct air capture, consume energy. Compared with other NETs, the value of energy produced by BECCS lies in the reduction of its net cost. BECCS implemented based on different biomass feedstocks may have different co-benefits, for example, BECCS based on algal biomass can produce both food and biofuels.

## 13.7 Barriers to implementation

### 13.7.1 Policy and regulatory environment

BECCS deployment requires a stable investment circumstance, especially in the condition of low carbon prices. Carbon prices can be changed by applying economic policy incentives. The lack of strong policy incentives is a major barrier to BECCS investment and deployment (Fridahl and Lehtveer, 2018; Muratori et al., 2016). In addition, policymakers can mitigate the risk of BECCS investment by providing subsides, tax credits for geological $CO_2$ sequestration, and price guarantee mechanisms.

Lack of political prioritisation is also identified as a barrier for implementing BECCS. Many countries have opened the door to use BECCS, however, have not provided sufficient emphasis and support for implementing this technology. In addition, some existing regulations may impede BECCS implementation, and a careful review and reform is required to improve the regulatory preconditions for BECSS deployment. For instance, current regulations in European Union (EU), such as EU’s *Emissions Trading System*, *Effort Sharing Regulation*, and *Land Use, Land Use Change, and Forestry Regulation*, do not allow an accounting of negative emissions from BECCS, and this creates BECCS deployment barriers (Nehler and Fridahl, 2022).

In Australian context, acknowledging BECCS as an eligible clean energy system is regarded as the first and most important step to underpin BECCS deployment in this nation (Pour et al., 2018). It was suggested that the existing schemes (such as the Emissions Reduction Fund, the Renewable Energy Target, and the National Carbon Offset Standard) and any future mitigation schemes in Australia need to include BECSS as one of eligible clean/renewable technology to support BECCS deployment. It was also suggested that Australia needs to recognise and reward negative emission through enacting policy schemes on carbon pricing, negative emission credit, and/or carbon tax.

### 13.7.2 Social licence and stakeholder acceptance

There are limited studies about social acceptance of BECCS as a negative emission approach to tackling climate change. Cox et al. (2020) investigated public perceptions of three carbon dioxide removal technologies (BECCS, direct air capture, and terrestrial enhanced rock weathering) in the United States and the United Kingdom. They found BECCS had the highest social acceptance among the three technologies. Bellamy et al. (2019) found their results on public perceptions of BECCS were largely consistent with those of separated BECCS components–bioenergy generation and CCS in the literature (e.g., Thomas et al., 2018; Upham and Roberts, 2011; Upham and Shackley, 2007) in the following points: (1) the public knows nothing or only a little about BECCS or CCS; (2) there are much more supports than oppositions to BECCS after the public obtains the required knowledge about BECCS; and (3) support for the biomass energy component of BECCS is higher than that for CCS component. Low social acceptance was also reported for multiple aspects of BECCS: biomass production, $CO_2$ separation, transportation, and storage, especially regarding $CO_2$ storage underground in several countries, such as in Germany (Dütschke et al., 2016; Fridahl and Lehtveer, 2018).

Public acceptance and support for BECCS are inextricably linked to their attitudes towards the policy incentives (Bellamy et al., 2019). To obtain social licence and stakeholder acceptance for deploying BECCS in Australia, we suggest that the government need to provide regulatory guidelines for action, produce strong policy incentives, and eliminate public concerns on negative environmental impacts of BECCS.

### 13.7.3 Technology performance variability

BECCS is a relatively complex technological system, encompassing any technological route of converting biomass to energy, capturing and storing $CO_2$ released upon this conversion in geological formations. Although BECCS technology is still evolving, the technological aspect is not a significant barrier to implementing BECCS. Key metrics to select a BECCS technological route include its cost, biomass conversion efficiency, $CO_2$ capture efficiency, and environmental impacts.

### 13.7.4 Financial proposition and costs and access to capital

To make large-scale deployment of BECCS economically viable, in a policy environment, the amount of $CO_2$ captured would require a net subsidy or bioenergy producers would need to be compensated for the carbon removal by growing their crops (Muratori et al., 2016). The subsidies for negative emissions need to provide to energy and land use sectors and be compensated by other sectors, for example, transport and industry (Bednar et al., 2019).

BECCS needs substantial upfront investment, therefore, creating incentives and financing propositions, reducing implementation costs, and accessing capital are critical for the commercialisation and deployment of BECCS. So far, incentives have been too low and unpredictable to attract investors. Therefore, there is a need for prompt creation of economic incentives, especially demand-pull incentives, to support commercialisation and large-scale deployment of BECCS. Uncertainties about BECCS implementation costs can also impede BECCS investment and deployment, a reliable cost estimation is a prerequisite for BECCS implementation.

### 13.7.5 Industry supply chains and skills

Industry supply chains and skills can be potential deployment barriers of BECCS. Every component in the industry supply chain can be a potential bottleneck for large-scale BECCS implementation, such as biomass or geological storage capacity availability. The level of technology skills throughout the industry supply chain of BECCS can also restrict the deployment of BECCS.

### 13.7.6 Market opportunities or market creation

Spontaneous market conditions are not mature at present. The current incentives have been too low and unpredictable to form effective market opportunities. BECCS market opportunities or market creation have to rely on political willingness, public acceptance, and policy incentives.

## 13.8 Scaling knowledge gaps:

Further efforts are required to address the following key questions related to knowledge gaps for the potential of BECCS deployment and overcoming BECCS implementation barriers in Australia.

1. What is maximum biophysically/technically potential for carbon dioxide removal via BECCS, and what is the attainable level of carbon dioxide removal via BECCS in Australia?
2. In Australia, how the BECCS technology can be deployed in a way which minimises its cost and impact on natural resources and ecosystems, while maximising both carbon removal and energy production?
3. What are the opportunities and costs (both environmental and socio-economic) for BECCS deployment in Australia?
4. What policy incentives are appropriate for BECCS to be deployed at scale in Australia?

## 13.9 Chapter References


ABARES, 2022. Snapshot of Australian Agriculture 2022, ABARES Insights: Canberra.

Almena, A., Thornley, P., Chong, K., Röder, M., 2022. Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass and Bioenergy 159 106406.

Beal, C.M., Archibald, I., Huntley, M.E., Greene, C.H., Johnson, Z.I., 2018. Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability. Earth's Future 6(3) 524-542.

Bednar, J., Obersteiner, M., Wagner, F., 2019. On the financial viability of negative emissions. Nature Communications 10(1) 1783.

Bellamy, R., Lezaun, J., Palmer, J., 2019. Perceptions of bioenergy with carbon capture and storage in different policy scenarios. Nature Communications 10(1) 743.

Bonsch, M., Humpenöder, F., Popp, A., Bodirsky, B., Dietrich, J.P., Rolinski, S., Biewald, A., Lotze-Campen, H., Weindl, I., Gerten, D., Stevanovic, M., 2016. Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy 8(1) 11-24.

Buck, H.J., 2016. Rapid scale-up of negative emissions technologies: social barriers and social implications. Climatic Change 139(2) 155-167.

Choi, Y.Y., Patel, A.K., Hong, M.E., Chang, W.S., Sim, S.J., 2019. Microalgae Bioenergy with Carbon Capture and Storage (BECCS): An emerging sustainable bioprocess for reduced CO2 emission and biofuel production. Bioresource Technology Reports 7 100270.

Clean Energy Council, 2008. Australian bioenergy roadmap - setting the direction for biomass in stationary energy to 2020 and beyond. Clean Energy Council.

Clean Energy Council, 2022. Clean Energy Australia Report 2022. https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2022.pdf.

Consoli, C., 2019. Bioenergy and carbon capture and storage. Global CCS Institute.

Cox, E., Spence, E., Pidgeon, N., 2020. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nature Climate Change 10(8) 744-749.

Crawford, D.F., O'Connor, M.H., Jovanovic, T., Herr, A., Raison, R.J., O'Connell, D.A., Baynes, T., 2016. A spatial assessment of potential biomass for bioenergy in Australia in 2010, and possible expansion by 2030 and 2050. GCB Bioenergy 8(4) 707-722.

DISER, 2021a. Australia's Long-Term Emissions Reduction Plan: Modelling and analysis. Australian Government Department of Industry, Science, Energy and Resources.

DISER, 2021b. Australian Energy Update 2021 Australian Energy Statistics: Canberra.

Dütschke, E., Wohlfarth, K., Höller, S., Viebahn, P., Schumann, D., Pietzner, K., 2016. Differences in the public perception of CCS in Germany depending on CO2 source, transport option and storage location. International Journal of Greenhouse Gas Control 53 149-159.

ENEA and Deloitte, 2021. Australia's Bioenergy Roadmap. Australian Renewable Energy Agency (ARENA).

Fajardy, M.C., 2020. Developing a framework for the optimal deployment of negative emissions technologies, Centre for Environmental Policy. Imperial College London, p. 260.

Fridahl, M., Lehtveer, M., 2018. Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. Energy Research & Social Science 42 155-165.

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., del Mar Zamora Dominguez, M., Minx, J.C., 2018. Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters 13(6) 063002.

Galik, C.S. A continuing need to revisit BECCS and its potential. Nat. Clim. Chang. 10, 2–3 (2020). https://doi.org/10.1038/s41558-019-0650-2

Gao, L., Bryan, B.A., 2017. Finding pathways to national scale land sector sustainability. Nature 544(7649) 217–222.

Global CCS Institute, 2021. Global status of CCS 2021: Australia.

Heck, V., Gerten, D., Lucht, W., Popp, A., 2018. Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nature Climate Change 8(2) 151-155.

IPCC. Special Report on Global Warming of 1.5 °C (eds Masson-Delmotte, V. et al.) (WMO, 2018).

Kanniche, M., Gros-Bonnivard, R., Jaud, P., Valle-Marcos, J., Amann, J.-M., Bouallou, C., 2010. Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO2 capture. Applied Thermal Engineering 30(1) 53-62.

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente Vicente, J.L., Wilcox, J., del Mar Zamora Dominguez, M., 2018. Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters 13(6) 063001.

Muratori, M., Calvin, K., Wise, M., Kyle, P., Edmonds, J., 2016. Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). Environmental Research Letters 11(9) 095004.

Nehler, T., Fridahl, M., 2022. Regulatory Preconditions for the Deployment of Bioenergy With Carbon Capture and Storage in Europe. Frontiers in Climate 4.

Ni, M., Leung, D.Y.C., Leung, M.K.H., Sumathy, K., 2006. An overview of hydrogen production from biomass. Fuel Processing Technology 87(5) 461-472.

Pour, N., 2018. BECCS sustainability, challenges, and potential, Department of Chemical Engineering. The University of Melbourne.

Pour, N., Webley, P.A., Cook, P.J., 2018. Opportunities for application of BECCS in the Australian power sector. Applied Energy 224 615-635.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534(7609) 631-639.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nature Climate Change 6(1) 42-50.

Thomas, G., Pidgeon, N., Roberts, E., 2018. Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom. Energy Research & Social Science 46 1-9.

Upham, P., Roberts, T., 2011. Public perceptions of CCS: Emergent themes in pan-European focus groups and implications for communications. International Journal of Greenhouse Gas Control 5(5) 1359-1367.

Upham, P., Shackley, S., 2007. Local public opinion of a proposed 21.5MW(e) biomass gasifier in Devon: Questionnaire survey results. Biomass and Bioenergy 31(6) 433-441.

UTAS, ANU, Common Captial, 2019. Capturing atmospheric carbon.

Whetton, P., Chiew, F., 2021. Chapter 12 - Climate change in the Murray–Darling Basin, In: Hart, B.T., Bond, N.R., Byron, N., Pollino, C.A., Stewardson, M.J. (Eds.), Murray-Darling Basin, Australia. Elsevier, pp. 253-274.

Williamson, P., 2016. Emissions reduction: Scrutinize CO2 removal methods. Nature 530(7589) 153-155.

# 14 Direct Air Capture

| | | |
|---|---|---|
| **Emission Type** | Avoided | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Figure 14-1: Direct air capture technology type**

## 14.1 Summary

**Description and current uptake**

Carbon dioxide ($CO_2$) is present in air at about 400 parts per million (ppm). Direct air capture (DAC) refers to the separation of $CO_2$ from air and its preparation for subsequent storage (carbon capture and storage, CCS) or use in further applications (carbon capture and utilisation, CCU). DAC may incorporate several process steps after $CO_2$ capture, including purification (removal of other, undesired gas and vapour components), compression and/or liquefaction and transportation to the storage or use location.

DAC generally uses technologies developed for $CO_2$ capture from point sources (such as power station flues). The technologies are based on differences between $CO_2$ and other air components in transport properties or their affinity to structured materials. The leading DAC technologies use either solid adsorbents or liquid absorbents. In both pathways CO2 would be released by an increase in temperature with the capture materials continuously re-used.

A 2021 report from the International Energy Agency (IEA) found that 19 operational DAC plants were capturing a total of more than 10 kt $CO_2$ per year, globally. However, under its Net Zero Emission by 2050 scenario, the IEA anticipated a DAC capacity of more than 85 Mt $CO_2$ per year by 2030 and 980 Mt $CO_2$ per year by 2050. To meet this scale-up challenge, a number of existing companies and organisations, worldwide and in Australia, are actively developing new $CO_2$ capture technologies and pilot plants. In addition to government funding and venture capital, business models include using captured $CO_2$ in diverse applications (such as synthetic e-fuel production, growth enhancement in greenhouses and beverage carbonation) or offering carbon removal services to other companies.

**Sequestration potential**

DAC is a capture technology that relies upon the sequestration potential of CCU and CCS.

**Challenges and opportunities for DAC**

Current costs for DAC are around \$600 per t $CO_2$, depending on the technology used. Equipment modularity, use of prefabrication methods with easy local assembly and the standardisation of processes are anticipated to result in significant cost reduction. Achievable savings determined over a range of learning rates and larger-scale deployment suggest cost levels could be between \$100 and \$200 per t $CO_2$.

The primary challenge for DAC is its high energy consumption, leading to high cost for this technology. The theoretical minimum energy requirement for separating $CO_2$ from an air stream is around triple that of capturing $CO_2$ from a power station flue. Energy is also required for movement of air through the capture devices. It is therefore essential for DAC to have access to low emission, low cost electricity sources. For example, using an electricity supply with an emission intensity of 0.1 per t $CO_2$ per MWh would result in $CO_2$ emissions between 0.1 and 0.25 t per t $CO_2$ captured. This would greatly reduce the effectiveness of a DAC plant. It is expected that as DAC technology matures and is implemented at scale, all systems will use electricity from renewable sources with very low emissions intensity.

DAC technology captures $CO_2$ using connected units which require significant land areas for adequate spacing. An energy supply (such as wind or solar) also takes up considerable space. Current liquid absorbent systems have significant water requirements as water is lost via evaporation in the $CO_2$ capture process. Some solid adsorbents are sensitive to water and a separate water removal process might be necessary; other solid adsorbents have the ability to capture both $CO_2$ and water.

**Social and environmental impacts, risks and co-benefits**

The environmental impacts of DAC technologies are the focus of increasing research. Life cycle analysis helps ensure the quality and integrity of carbon credits produced by DAC and provides useful insights into local environmental impacts (e.g., related to handling of wastes and emissions to the atmosphere), and global effects. Recent life cycle analysis of an industrial DAC process indicated that carbon capture efficiencies of greater than 90% could be realised, depending on the energy source.

DAC application can provide new services (carbon credit trading) and new products (carbon neutral products), generating new economic productivity and employment opportunities. The availability of low cost DAC might be advantageous for a variety of existing applications where fossil-fuel-derived $CO_2$ is currently used.

**Scaling knowledge gaps**

While several start-up companies already deploy DAC technology, key questions remain. These focus on aspects of energy consumption (lowering consumption and identifying preferred energy source), ways to lower the land area requirement, and issues to do with public perception of DAC and any environmental impacts.

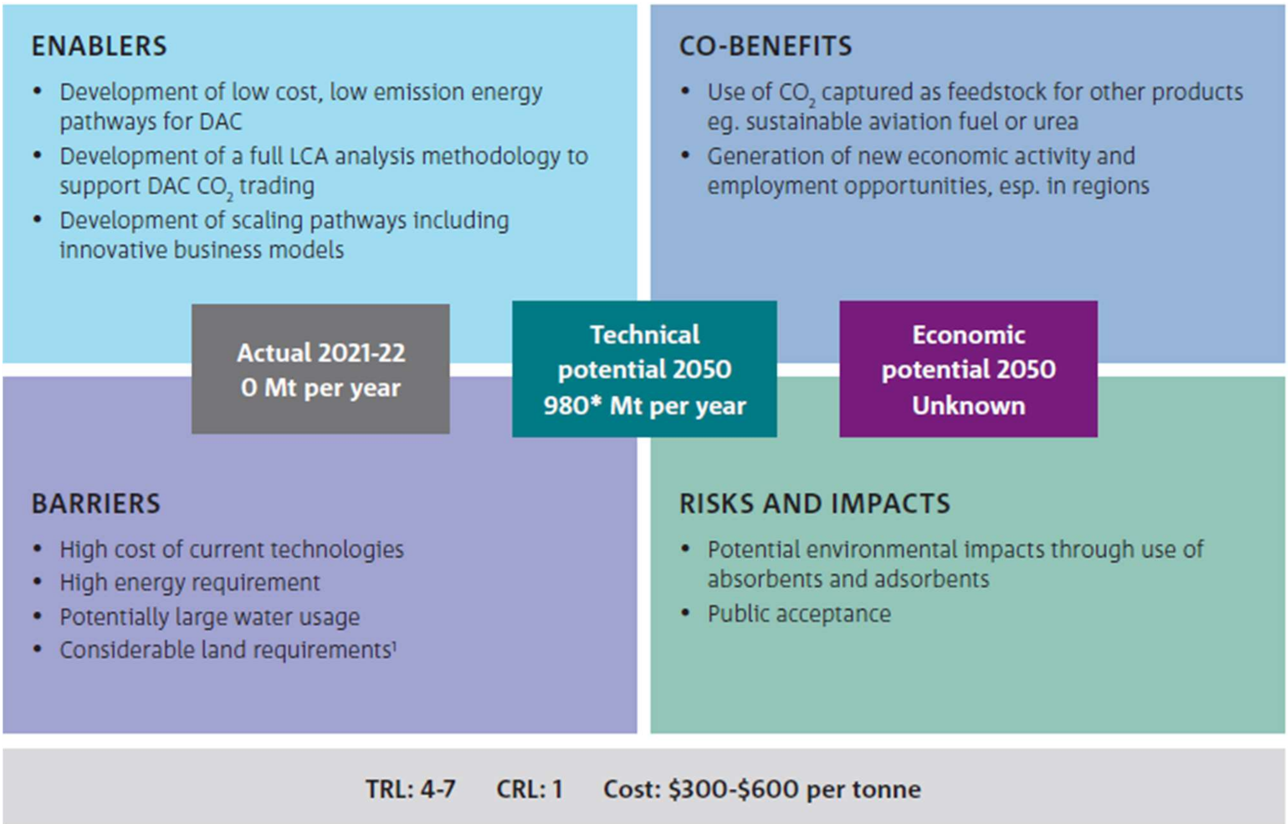



**Figure 14-2: Summary of direct air capture – note direct air capture is a capture technology. *IEA estimate globally for 2050. [1]Significantly less than afforestation.**

## 14.2 Description and current uptake

Direct air capture (DAC) refers to the extraction or removal of carbon dioxide from air (~ 400 ppm) using an engineered device and the provision of the carbon dioxide product at the required purity to a storage facility (CCS= $CO_2$-capture and storage) or a use application (CCU= $CO_2$-capture and utilisation). DAC may incorporate several process steps starting with the separation of $CO_2$ from the air, its purification (removal of other, undesired gas and vapour components, such as water) as needed for subsequent steps, its compression and/or liquefaction and transportation to the use or storage location. DAC has the benefit of being able to capture $CO_2$ anywhere, anytime thus avoiding a large expense on transportation infrastructure. The lack of infrastructure that can connect $CO_2$ emissions sources with $CO_2$ storage locations is an obstacle to deploying $CO_2$-capture and storage technology. While DAC plants can be located close to suitable $CO_2$-storage locations and use facilities they will require access to a low emission and low cost energy supply.

### 14.2.1 Separation technologies for DAC

Technologies developed for $CO_2$-separation from point sources, such as industrial gases and flue gases are generally applicable for DAC purposes. They are often based on differences in affinity and/or transport properties of $CO_2$ and other air constituents with respect to structured materials. Also, differences in the physical properties for air constituents may be used to separate CO2, as is the case in refrigeration processes, where differences in freezing and condensation temperature are exploited for component separation. Absorption, adsorption and membranes are examples of such technologies that use other materials to separate CO2.

Compared to capture from point sources, such as flue gases from power plants, DAC has the following challenging attributes:

- Larger volumes of gas (air) need to be treated at a given $CO_2$-production. This leads to the use of much larger equipment and, therefore higher capital cost and increased additional energy for movement of the air through the capture devices.
- The regeneration of the capture agent is more energy intensive as it needs to be able capture again in the next use cycle and therefore requires a deeper level of regeneration. with much lower effectiveness, necessitating modifications to the process design and equipment or development of dedicated capture agents.

### 14.2.2 Leading DAC technologies

The leading DAC separation technologies either use solid adsorbents or liquid absorbents to capture $CO_2$.

Solid adsorbents typically use porous materials to achieve high surface area for contact with air. The materials are often functionalised using amines to create a large affinity for $CO_2$. After adsorption, the material is heated up, releasing $CO_2$ at moderate temperatures (80-120 $^oC$), after which the material can re-adsorb $CO_2$ as part of the cyclic process. Solid adsorbents are the core technology for the two out of three leading DAC companies, i.e., Switzerland based Climeworks (founded in 2009) and United States based Global Thermostat (founded in 2010), with both using proprietary amine-based materials that can reversibly capture and release $CO_2$.

Liquid absorbents are based on aqueous solutions that contain alkaline salts that will subsequently react with the weak acid $CO_2$. Carbon Engineering has pioneered this approach using sodium or potassium hydroxide solutions in cooling towers where the carbonate produced is reacted with calcium oxide to form calcium carbonate. $CO_2$ is then released in a calcination process at high temperature (900 $^oC$).

Membranes are mostly applicable in combination with liquid absorbents as gas/liquid contactors, where they can provide high surface area for gas/liquid exchange. Selective membranes are generally ineffective for DAC because of the very low CO2-concentration in air, that results in low CO2 product purity and large membrane area requirements. Refrigeration processes have also not been used in DAC processes, most likely of the high energy demands associated with cooling of large air volumes.

### 14.2.3 DAC technology status

The International Energy Agency (IEA), in its latest tracking report on DAC (November 2021)[29] states that 19 operational DAC plants are capturing more than 10 kt $CO_2$ per year in total. In its Net Zero Emission by 2050 scenario, the agency anticipates that 980 Mt per year DAC capacity is needed by 2050, with more than 85 Mt per year by 2030. By comparison, 27 operational large-scale CCS projects are currently capturing 40 Mt per year $CO_2$[30] from point sources. Hence DAC technology development and deployment must significantly increase and address the scale-up challenge.

Carbon Engineering is most advanced in terms of technology scale-up. In partnership with 1PointFive, a development company formed by Oxy Low Carbon Ventures, Carbon Engineering are jointly conducting a Front End Engineering and Design (FEED) study for the first large-scale, commercial Direct Air Capture[31]

---

[29] https://www.iea.org/reports/direct-air-capture

[30] Global status of CCS 2021 – CCS accelerating to net zero, Global CCS Institute, 2021

[31] The Story Behind Carbon Engineering | Carbon Engineering

facility. Located in the Permian Basin, U.S., this facility is targeted to capture 1 Mt per year CO2 from the air annually with $CO_2$ stored underground in geological formations. Construction is anticipated to begin in the second half of 2022, and start-up in late 2024. Building on this progress, 1PointFive also presented its deployment approach to help execute large numbers of DAC projects globally. This deployment approach involves design standardisation of DAC plants to help deliver complete, operationally ready DAC facilities to local partners. Through this process, plant components and equipment will be modularised, mass manufactured and then assembled on-site using an established supply chain of vendors. 1PointFive announced a scenario of deploying 70 DAC facilities by 2035, each with an expected capacity of up to 1 million tonnes per year, under current policy and voluntary and compliance market scenarios.

**Case Study**: Orca-Iceland.
Climeworks has delivered most of the currently operating DAC plants (15) with the largest one, "Orca", operating in Iceland capturing 4 kt per year $CO_2$ with the product $CO_2$ mineralised in a geothermal well in collaboration with Carbfix. Smaller ones have delivered $CO_2$ for use in greenhouses, sustainable aviation fuel production or for carbonating beverages. Most recently, Climeworks announced they would be scaling up to 36 kt per year $CO_2$ in the "Mammoth" project. Climeworks has also pioneered a business model based on the provision of carbon removal services to companies and individuals. Climeworks raised 600 million CHF (650 million USD) in equity funding for the next growth phase, that involves scaling up their DAC technology to multi-million ton capacity. According to Bloomberg this represented the largest investment in a DAC technology to date[1] and came on top of 560 million USD investments into DAC technologies made by private entities since 2017

Three US locations will be considered to advance commercial adoption for CO2 sequestration and CO2 utilisation such as producing carbon neutral synthetic e-fuels, and for carbon negative power generation applications. Global Thermostat has realised pilot plants up to the scale of 4 kt per year CO2, and their engineering partner Black & Veatch were awarded US Department of Energy funding in 2021 to design a 100 kt per year DAC plant. Global Thermostat collaborates with Exxon Mobil and has another project in Chile where they will supply $CO_2$ to an e-fuels plant operated by HIF Global.

Figure 14-3 summarises the required growth trajectory, including the announced larger-scale plants from Climeworks and Carbon Engineering to be realised over the next three years.

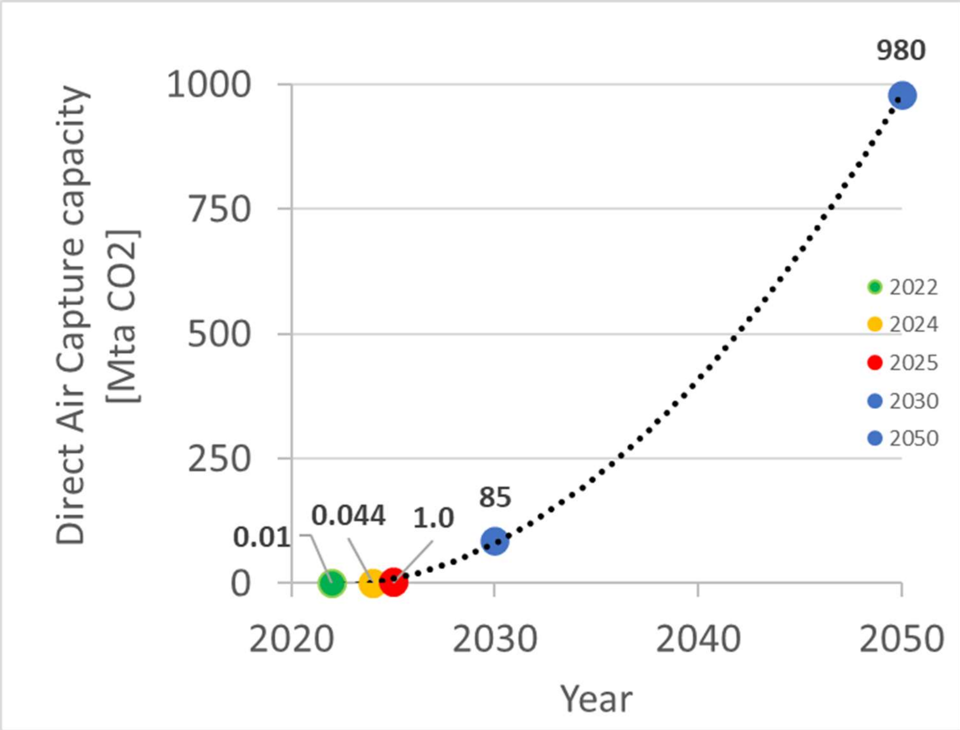



Figure 14-3: **DAC capacity growth trajectory according to IEA Net Zero Emission 2050 scenario and current/near term project plans**

Several other start-up companies have entered the DAC field. Some have received significant venture capital or are participating in the X-Prize competition[32]. Some companies also generate carbon removal credits that generate a cashflow as clients are willing to pre-pay the carbon credits. Carbon Engineering (411,580 credits) and Climeworks (16,690 credits) are market leaders in DAC carbon credits. Recently, Aspiradac became the first Australian company to secure funding through prepayment of the generation of carbon credits using DAC[33].

A non-exhaustive overview of DAC technology providers is given in Table 14-1. In addition, CSIRO is developing three different technologies, CarbonAssist (https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/carbonassist), AirThena (https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/co2gen), both based on proprietary solid adsorbent structures and ACOHA (https://www.csiro.au/en/research/environmental-impacts/emissions/ambient) based on proprietary liquid absorbents. This research may result in the launch of further start-up companies.

**Table 14-1: Overview of DAC technology providers[34]**

| Capture agent | Company | TRL[35] | Comments |
|---|---|---|---|
| **Liquid absorbent** | Carbon Engineering | 7 | TRL likely to reach 9 by 2025 |
| **Solid adsorbent** | Climeworks | 7 | TRL likely to reach 8 by 2024 |
| **Solid adsorbent** | Global Thermostat | 7 | TRL likely reach 8 by 2024 |

[32] https://www.xprize.org/prizes/elonmusk

[33] https://www.theguardian.com/environment/2022/jul/02/australian-company-secures-700000-deal-for-carbon-capture-and-storage-machine

[34] Life cycle and techno-economic assessments of direct air capture processes: An integrated review, Remi Chauvy, Lionel Dubois, Int J Energy Res. 2022;1–25

[35] Author assessment

| | | | |
|---|---|---|---|
| **Solid adsorbent** | Soletair | 6 | Temperature/Vacuum swing process; Air conditioning application |
| **Solid adsorbent** | Infinitree | 4 | Humidity swing process; CO2 to greenhouses |
| **Solid adsorbent** | Skytree | 4 | Spun out of European Space agency |
| **Solid adsorbent** | Verdox | 4 | Electrical swing process; XPrize Milestone prize winner |
| **Solid adsorbent** | Sustuera | 4 | Alkali metal based capture agent; X-Prize Milestone prize winner |
| **Solid adsorbent** | Carbyon | 4 | Carbon fibres functionalised with amines; X-Prize Milestone prize winner |
| **Solid adsorbent** | Carbon Collect | 4 | Regeneration under vacuum; Passive system |
| **Solid adsorbent** | Aspiradac | 4 | Metal-organic-framework based; DAC integrated with photovoltaic system |
| **Solid adsorbent** | Kawasaki Heavy Industries | 4 | Moving bed system adapted from flue gas application; use of waste heat |
| **Solid adsorbent** | Heirloom | 4 | Calcium looping system with high temperature regeneration |
| **Liquid absorbent** | CO2Circulair | 4 | Membrane gas absorption; regeneration using electrodialysis |

## 14.3 Sequestration Potential

The sequestration potential for direct air capture is constrained by the cost of the technology, the energy requirements and the land and water availability. These challenges are described in more detail below.

| Estimate of capture | Sequestration ($Mt.yr^{1}$) | Key evidence |
|---|---|---|
| **Potential** | Determined by potential for sequestration | See sequestration sections |
| **Economic potential by 2025** | 1.0 | Based on Carbon Engineering business plans |
| **Economic potential by 2035** | 210 | Interpolated from IEA report[10] |
| **Economic potential by 2050** | 980 | IEA report[10] |

**Table 14-2: Best estimate of DAC sequestration potential noting that sequestration is dependant on sequestration technology.**

## 14.4 Challenges and opportunities for DAC[36,37]

### 14.4.1 Cost

Current costs for DAC are around $\$600.t^{-1}$ CO2, depending on the technology type. In addition to large equipment size and significant energy consumption, this cost reflects the small-scale of application. The technology developers indicate that costs can be significantly reduced to $\$125.t^{-1}$ $CO_2$ and $335.t^{-1}$ $CO_2$ for large-scale plants with further reductions driven by technology deployment and innovation. Equipment

[36]Lebling, K., H. Leslie-Bole, P. Psarras, E. Bridgwater, Z. Byrum, and H. Pilorgé. 2022. "Direct Air Capture: Assessing Impacts to Enable Responsible Scaling." Working Paper. Washington, DC: World Resources Institute. Available online at https://doi.org/10.46830/wriwp.21.00058

[37] Direct Air Capture - A key technology for net zero, IEA, April 2022

modularity, high volume manufacturing, use of prefabrication methods with easy local assembly and the standardisation of these processes are anticipated to result in significant cost reduction. The cost reduction is quite like the achievement of cost reductions when scaling up photovoltaic and wind energy conversion devices. Achievable costs determined over a range of learning rates and large-scale of deployment indicate cost levels between \$100.$t^{-1}$ $CO_2$ and \$ 200.$t^{-1}$ $CO_2$ (McQueen et al, 2021), (Lackner and Azarbadi, 2021).

### 14.4.2 Energy

The energy consumption for DAC is of concern as the theoretical minimum energy requirement for the separation of CO2 from an air stream is around three times higher compared to $CO_2$-capture from a flue gas in a power station. A simplified overview of the estimated energy consumption for the leading DAC technologies is given in Table 2 (IEAG, 2021) for "First-of-a-Kind" and Nth-of-a-Kind" systems, i.e. after further development and deployment. It is expected that longer term all systems will be using electricity only, to provide easy connection with renewable energy generation that will most likely deliver electricity into grid systems or stand-alone systems. The estimates in Table 14-3 do not include the energy requirements for storage or use.

**Table 14-3: Overview of energy consumption for DAC systems in comparison to CO2-capture from power stations**

| | Liquid absorbent First of a Kind | Liquid absorbent $N^{th}$ of a Kind | Solid adsorbent First of a Kind * | Solid adsorbent $N^{th}$ of a kind * |
|---|---|---|---|---|
| **Thermal Energy ($GJ.t^{-1}$ CO2)** | 6.8 | 0 | 10.8 (0) | 4.9 (0) |
| **Electrical Energy ($GJ.t^{-1}$ CO2)** | 2.2-3.7 | 7.2-9 | 2.3 (6.6) | 1.6 (3.6) |

*) Numbers in brackets refer to use of heat pump in solid adsorbent systems

For the $N^{th}$-of-a-kind systems in Table 14-3 that only use electrical energy the energy requirement ranges between 3.6 and 9.0 $GJ.t^{-1}$ $CO_2$ (equivalent to 1.0-2.5 $MWh.t^{-1}$ $CO_2$). At a very low cost of electricity of say \$10/MWh this would contribute \$10-25 per tonne CO2 to the capture cost.

For the projected range of electricity requirements for DAC, it would also be essential to have access to low emission electricity sources. For example, an electricity supply with an emission intensity of 0.1 t $CO_2$/MWh would result in a $CO_2$-emission between 0.1 and 0.25 $t.t^{-1}$ $CO_2$-captured; the latter would reduce the effectiveness of the DAC plant significantly. Renewable and nuclear energy sources are therefore preferred for the electricity supply.

### 14.4.3 Land availability

DAC is a distributed technology, i.e. $CO_2$ is captured by many connected devices, which require significant land areas for adequate spacing of the capture units. The (renewable) energy supply, for example, using photovoltaic systems or wind turbines, will also take up considerable space. However, the land area requirement is at least 100 times less than afforestation at the same carbon removal.

### 14.4.4 Water

Current liquid absorbent system will have significant water use as water is lost via evaporation in the $CO_2$-capture process. Water consumption can range from 0 to 9 tonnes per ton $CO_2$ removed for the Carbon

Engineering technology, depending on absorbent concentration and air temperature/humidity (Keith et al, 2018). This might limit the applicability in dry climates, like Australia. Some solid adsorbents are sensitive to water and separate water removal might be necessary. Other solid adsorbents can capture both $CO_2$ and water, which is advantageous. Climeworks indicates that their technology could capture 1 ton water per ton $CO_2$ (Beuttler and Wurzbacher, 2019)

## 14.5 Social and Environmental Impacts, Risks and co-benefits

### 14.5.1 Environmental impacts

The environmental impacts of DAC are the focus of increasing research. An extensive life cycle analysis has recently been published for the Climeworks technology (Deutz and Bardow, 2021). This study indicated that high carbon capture efficiencies (>90%) could be realised but these were quite dependent on the energy source. Life cycle analysis is crucial to ensure the quality and integrity of the carbon credits produced by DAC technology. It also provides valuable insights into local impacts, e.g., related to the handling of wastes and emissions to the atmosphere, and global effects, e.g. capture agent supply chains, when large-scale rollout is considered. Research results will flow into regulatory requirements.

### 14.5.2 Socio-economic impacts

DAC applications can provide new services (carbon credit trading) and new products (carbon neutral products), generation new economic productivity and employment opportunities. Manufacturing, assembly and maintenance of DAC units and the associated infrastructure related to the energy supply and $CO_2$-handling will create new blue-collar jobs.

### 14.5.3 Co-benefits

The availability of low cost DAC might be advantageous for a variety of existing applications where fossil-fuel-derived $CO_2$ is currently used. Examples are growth enhancement in greenhouses or the use of $CO_2$ in carbonated beverages. There is also significant potential for $CO_2$ as a feedstock for sustainable aviation fuels, renewable methane and renewable chemicals e.g. urea if renewable sources meet the energy requirements. Using air as a $CO_2$ resource facilitates the development of local industries close to markets for $CO_2$-neutral products and services.

### 14.5.4 Scaling knowledge gaps

DAC technology is currently developed and simultaneously deployed by several start-up companies. Key questions are:

1. What is the lowest energy consumption achievable?
2. What is the minimum land area requirement?
3. Is there a preferred energy source to power DAC?
4. Is there a preferred DAC technology pathway for Australia?
5. What are the environmental impacts, positive and negative, beyond greenhouse gas removal?
6. Will the public perception of DAC be an obstacle to uptake?

# 14.6 Chapter References


Beuttler C, Charles L and Wurzbacher J (2019) The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. Front. Clim. 1:10. doi: 10.3389/fclim.2019.00010

Deutz S and Bardow A, Life cycle assessment of an industrial direct air capture process-based on temperature–vacuum swing adsorption, Nature Energy, VOL 6, February 2021, 203–213

IEAGHG "Global Assessment of Direct Air Capture Costs", 2021-05, December 2021.

Keith et al., A Process for Capturing CO2 from the Atmosphere, Joule (2018), https://doi.org/10.1016/j.joule.2018.05.006

Lackner K. and Azarabadi H, Buying down the Cost of Direct Air Capture, Industrial & Engineering Chemistry Research 2021 60 (22), 8196-8208

Lebling, K., H. Leslie-Bole, P. Psarras, E. Bridgwater, Z. Byrum, and H. Pilorgé. 2022. "Direct Air Capture: Assessing Impacts to Enable Responsible Scaling." Working Paper. Washington, DC: World Resources Institute. Available online at https://doi.org/10.46830/wriwp.21.00058

McQueen N., Vaz Gomes K., McCormick C., Blumanthal K., Pisciotta M. and Wilcox J. ,Prog. Energy 3 (2021) 032001

# 15 Mineral Carbonation and Enhanced Weathering

| | | |
|---|---|---|
| **Emission Type** | Avoided | Negative |
| **Enabling Capture Technology** | Biological | Engineered |
| **Enabling Storage Technology** | Biological | Engineered |

**Figure 15-1: Mineral Carbonation technology type**

## 15.1 Summary

**Description and current uptake**

Mineral carbonation and enhanced weathering are chemical processes of where CO2 is captured from the atmosphere and reacts with minerals. In mineral carbonation, $CO_2$ (as a gas or dissolved in water) reacts with minerals containing calcium (Ca) and magnesium (Mg) to form stable Ca and Mg-carbonate minerals. This results in the $CO_2$ being geologically stored in minerals and removed from the atmosphere. In the process of enhanced weathering, silicate minerals react with $CO_2$ in water to break down, but the $CO_2$ stays dissolved in water as dissolved inorganic carbon (DIC). Dissolved inorganic carbon enters the water cycle and eventually is washed into the ocean, removing $CO_2$ from the atmosphere.

Both processes occur naturally as part of the global carbon cycle, however, for carbon sequestration these reactions need to be sped up. Engineered solutions can increase the rate of atmospheric $CO_2$ removal and present an opportunity to fix $CO_2$ in long-term geological storage or incorporate the resulting carbonates in industrial products (such as concrete and plasterboard).

Many different minerals can be used for mineral carbonation and enhanced weathering. The most feasible target rocks are mafic and ultramafic rocks, which contain high to very high concentrations of Mg, respectively. These are present across Australia in significant volumes.

In in-situ mineral carbonation, $CO_2$ is injected into the high-Mg target rocks and the chemical reactions take place underground (in the subsurface). In ex-situ mineral carbonation, $CO_2$ reacts with extracted material (such as crushed rock, smelter slag, fly ash or cement kiln dust) above-ground and the chemical reactions take place in a controlled industrial process.

At present, there is only demonstration-scale technology available for mineral carbonation. There is no current Emissions Reduction Fund (ERF) method related to mineral carbonation. In addition, there has been little attention paid to enhanced weathering in Australia as its many arid and semi-arid regions have low rates of natural weathering.

**Sequestration potential**

The conversion degree of $CO_2$ varies by rock type, particle size, reaction conditions (e.g. temperature, pressure, acidity) and time. Passive mineral carbonation into tailings at Mount Keith Mine in Western Australia occurs by reaction of atmospheric $CO_2$, with only 1% of the tailings material carbonated per annum. This rate of mineral carbonation could be increased if engineering solutions are applied at the site. Other studies have reported that for a pilot test, 95% of injected $CO_2$ could become a carbonate mineral in less than 2 years. Global estimates of $CO_2$ sequestration via mineral carbonation (using certain rock types) range between 1.1 and 4.5 Gt per year. In Australia the potential is estimated as 36Mt per year by 2050 at a cost of between $28 - $300 per tonne.

Potential sequestration of carbon through ex-situ mineral carbonation could be explored at currently operating or closed mines, with geologically suitable waste rock or tailings. These are found around Australia; however, a complete inventory of volumes and mineralogy would need to be done to estimate sequestration potential with confidence.

Enhanced weathering can be promoted by soil amendments (adding materials that change soil properties), which may simultaneously produce DIC and stimulate biotic action (activities due to living things) in the soil. Modelling has suggested that adding basalt dust to some ecosystems can improve soil fertility and enhance $CO_2$ storage.

**Technology readiness potential and commercial readiness**

It is difficult to assess the technology readiness of mineral carbonation due to the lack of data and limited pilot studies. However, around the world a number of industry and research groups are moving forward in the mineral carbonation landscape. In Australia, funding has been awarded to Mineral Carbonation International and Boral Limited for projects focusing on mineral carbonation for carbon capture and use (CCU) in producing materials for manufacturing and construction.

In late June 2022, the Western Australia Government announced that it will develop a roadmap for integrated mineral carbonation. In addition, CSIRO has recently launched a permanent carbon locking platform (CarbonLock), which aims to drive innovation in carbon capture and carbon storage. These investments and initiatives indicate the future potential of mineral carbonation capacity.

**Scaling knowledge gaps**

The main challenge for mineral carbonation is that it is slow, whether performed in-situ or ex-situ. Further research is required to assess the potential for carbon sequestration through carbon mineralisation. The maturity of the research is variable, and more understanding is needed to make valid judgements on storage capacities, the rates of mineral carbonation reactions in an industrial setting and the practicability of the technology in Australia.

**ENABLERS**

- Research to improve reaction rates and lower costs
- Research to identify location and quantities of feedstock
- Research to demonstrate and expand the use of mineral carbonation derived product materials
- Establish an exemplar

**CO-BENEFITS**

- Makes use of tailings as a value stream to generate new mineral carbonation products

**Actual 2021-22**
**0.1 Mt per year**

**Technical potential 2050**
**36 Mt per year**

**Economic potential 2050**
**Unknown**

**BARRIERS**

- Ex-situ: Cost of grinding and transporting feedstock material
- Low reaction rates requiring excess feedstock
- Lack of mapping suitable locations
- Access to sufficient raw materials

**RISKS AND IMPACTS**

- Ex-Situ, generation of possible harmful by products
- In-Situ: Increased seismicity and potential groundwater contamination

**TRL: 5-7 CRL: 1 Cost: $28-$30 per tonne Length of storage: >1000 years**

**Figure 15-2: Summary of mineral carbonation and enhanced weathering.**

## 15.2 Description and current uptake

Mineral carbonation and enhanced weathering is a chemical sequestration technology.

Carbon dioxide ($CO_2$) can be removed from the atmosphere by reacting it with minerals containing calcium (Ca), magnesium (Mg) combined with varying proportions of silicon (Si) and oxygen (O). These Ca- and Mg-silicate minerals dissolve, react with the $CO_2$, either as a gas or dissolved in water, and stable Ca and Mg-carbonate minerals are precipitated in their place. During this process, a whole family of minerals is produced which contain both $CO_2$ and water locked within their crystal structure. For example, when the Mg-silicate mineral olivine ($Mg_2SiO_4$) reacts with $CO_2$ it can produce the Mg-carbonate mineral magnesite ($MgCO_3$) by the following reaction:

Equation 1: $Mg_2SiO_4$ (s) + $2CO_2$ (g) = $2MgCO_3$ (s) + $SiO_2$ (s), g=gas; s=solid

In this reaction $CO_2$ is fixed geologically in a mineral phase removing it from the atmosphere.

Alternatively, the $CO_2$ may stay dissolved in water during the mineral breakdown reaction where it is referred to as dissolved inorganic carbon (DIC) and enter the water cycle eventually being washed into the ocean. For example, when the Ca-silicate mineral wollastonite ($CaSiO_3$) breaks down to dissolved (aqueous, aq) Ca and produces silicon oxide as quartz:

Equation 2: $CaSiO_3$ (s) + $H_2O$ (l) + $2CO_2$ (g) = $2HCO_3^-$ (aq) + $Ca^{2+}$ (aq) $SiO_2$ (s), aq=aqueous; l=liquid

Both processes, the fixing CO2 as minerals and the production of DIC, occur naturally and are part of the global carbon cycle. However, engineered solutions to increase the rates of atmospheric $CO_2$ removal present an opportunity to fix $CO_2$ in long-term geological storage reservoirs. Human induced fixing of $CO_2$ in carbonate minerals is referred to as *mineral carbonation* while promoted weathering of silicates to dissolved inorganic carbon (DIC) is discussed as *enhanced weathering.*

There are abundant Mg-Ca silicate-bearing rocks in Australia, and many different minerals can be used for mineral carbonation and enhanced weathering including olivine, serpentine, wollastonite and Ca-bearing feldspar minerals. Mineral dissolution rates, which potentially control the rate of the process, vary with mineral type. Generally, the more rapidly dissolving minerals (e.g. brucite) are less abundant in the Earths' crust while the minerals that are widely available are much slower and present significant challenges as sinks for $CO_2$.

### Mineral Carbonation

There are two approaches to mineral carbonation: in-situ and ex-situ (Oelkers et al., 2008). In-situ mineral carbonation requires $CO_2$ to be injected into rocks that are contain high proportions of the Ca- and Mg-silicate minerals with which the $CO_2$ will react. The most abundant targets are rocks that contain high (mafic rocks) or very high (ultramafic rocks) concentrations of Mg and the easiest minerals to dissolve serpentine, brucite and olivine. For example, peridotite is an ultramafic rock composed of the mineral serpentine or basalt, which is a mafic rock containing minerals such as olivine. The chemical reactions occur underground (in the subsurface) and result in the $CO_2$ being locked geologically as carbonate minerals (e.g. equation 1 above). The success of this approach relies on detailed understanding of the subsurface geology, engineering and monitoring controls to ensure the $CO_2$ is retained long enough to allow reactions to occur at relatively modest temperatures. However, the upside is considerable since there are large volumes of mafic and ultramafic rocks across Australia.

Ex-situ mineral carbonation is achieved using extracted material, e.g., crushed rock or industrial products like smelter slag, fly ash or cement kiln dust (Kelemen, 2020), in a separate reactor or other industrial process, e.g., mine tailings dam, where the operational conditions are controllable and reaction rates may be increased by manipulating the chemical environment, particle size and other factors. Engineering solutions required to drive sustained mineral carbonation processes are complex (Kelemen et al., 2020).

### Enhanced Weathering

Soil amendment, addition of material to soil to change its properties, leads to enhanced weathering that removes $CO_2$ from the atmosphere as the silicate minerals weather to produce dissolved inorganic carbon (DIC). Biotic action in the soil can simultaneously improve the soil quality leading to benefits beyond the carbon drawdown. The choice of material is governed by supply, reactivity, ability to produce DIC and negative effects of weathering on the pasture or croplands e.g., release of toxic metals into the ecosystem.

## 15.2.1 Challenges of in-situ mineral carbonation

Achieving large volumes of in-situ mineral carbonation requires suitable porous and permeable rock and the ability to maintain this permeability during the $CO_2$-rock reaction. Highly porous rocks provide a large reactive surface area and permeable pathways that allow the transport of $CO_2$ in either gaseous form or solution through a rock with mineralogy that is favourable for carbonation (e.g., McGrail et al., 2006). Commercial pilot projects, such as CarbFix operating in Iceland, use young, porous, highly fractured basalt target rocks for mineral carbonation where injected $CO_2$ can flow easily though large rock volumes. Rock in Australia are generally older and less permeable so creating and maintaining permeability remains a challenge. The chemical reactions resulting in mineral carbonation can occur at relatively low temperatures (e.g., Beinlich, 2020). Rocks favourable to mineral carbonation processes and that are abundant in Mg-Ca silicates include ultramafic and some mafic rocks (e.g. Figure 15-3) although some sedimentary rocks may also be favourable (Kelemen, 2020).

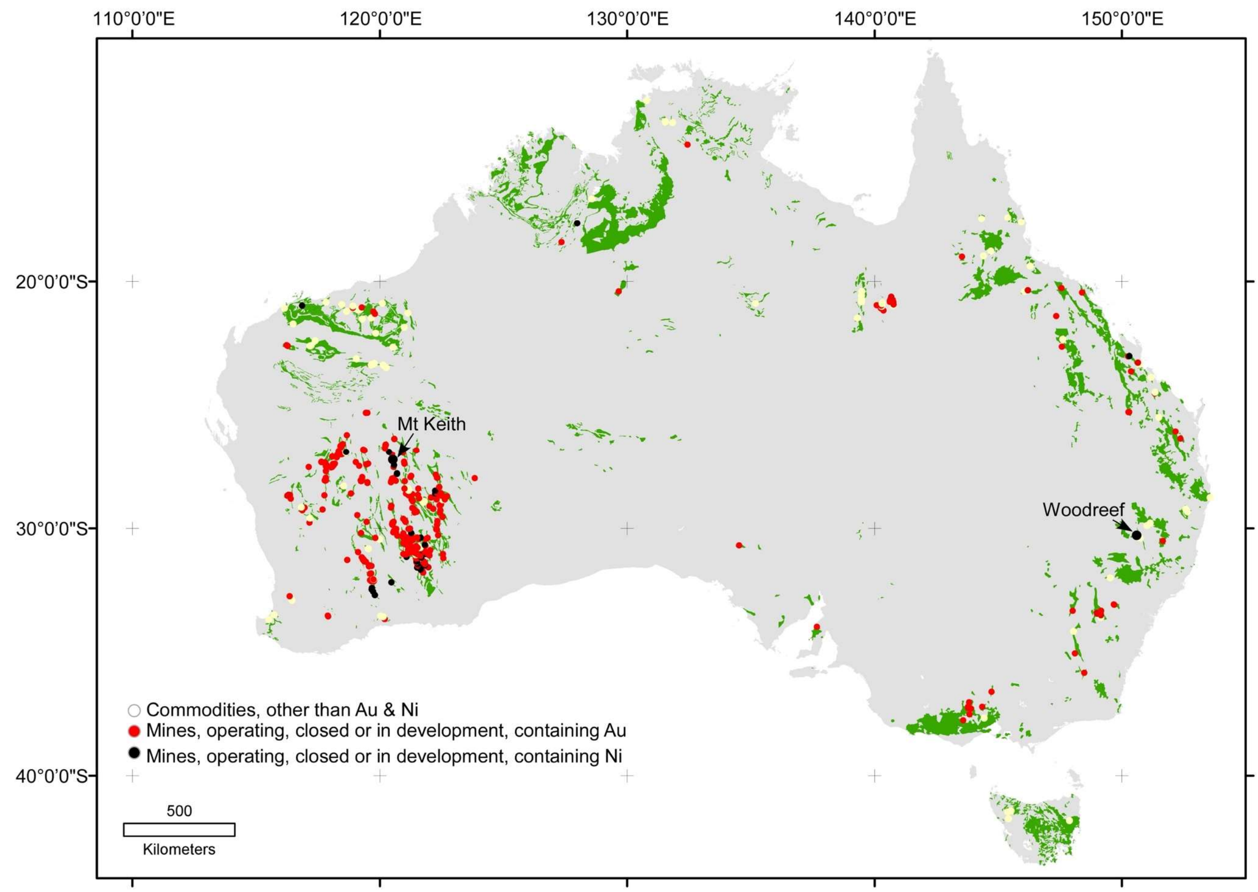



**Figure 15-3: Map of Australia illustrating regions which may contain exposed mafic or ultramafic rocks (in green) overlain by known mines in these areas, operating, closed or in development (adapted from Geoscience Australia 1:2.5m surface geology, 2012)**

Maintaining porosity and permeability during in-situ mineral carbonation processes is problematic because volume increases are associated with the mineralisation. For example, the reaction that produces magnesite ($MgCO_3$) and quartz ($SiO_2$) results in a volume change of approximately 34 $cm^3$ per mole, compared to the sequestration of carbon through reaction of carbon dioxide with brucite that produces only a modest volume change of ~2 $cm^3$ per mole. Thus, although carbon mineralisation involves relatively simple chemical reactions, it may be stifled in natural systems simply due to restricting the porosity and permeability in the rock materials, preventing more reactions. These problems are made worse when hydrated minerals such as hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$), are present.

### 15.2.2 Challenges of ex-situ mineral carbonation

To scale-up mineral carbonation, more reactive materials are required but crushing is extremely energy intensive and increased emissions, possibly related to the source of energy used, will offset large amounts of the $CO_2$ drawn down by mineralisation. Fine particle sizes produced by crushing rocks during mineral processing, associated with ore extraction at mining operations, provide large reactive areas for mineral carbonation, hence the focus on using mine tailings and other waste products such as fly ash and cement kiln dust. The slow natural reaction rate between ultramafic tailings and atmospheric $CO_2$ requires extended exposure of the tailings to the atmosphere for even the most reactive component, brucite, to fully react (Wilson et al., 2014). Slowing tailings production by reducing mine throughput has an economic impact on the mine so other solutions need to be found to take full advantage of the brucite mined.

Reaction rates can be accelerated by reacting the tailings material with fluids that have a higher $CO_2$ content than the atmosphere (Harrison et al, 2013). The $CO_2$ can come from redirected flue gas or direct air capture, the challenges of which are outlined elsewhere in this report. Engineering solutions are then required to inject the $CO_2$, either as gas or dissolved in water, with the reactant material. The tailings' natural permeability is very low, so injection (and energy) is required to drive flow through the tailings material. The process may be enhanced by engineering particle size distributions using waste rock but there is still the potential for clogging due to the large positive volume change of reactions discussed above.

Long-term stability of some of the Mg-carbonates produced is not well established. While injecting $CO_2$ into rocks at higher temperatures (e.g. 130°C) leads to just magnesite being produced (equation 1; Voigt et al., 2021), reactions between Mg-silicates and $CO_2$ at atmospheric temperatures produces a range of carbonate minerals (e.g. Wilson et al., 2009), some of which contain water within their crystal structure. Long-term storage solutions for the reacted tailings material may lead to increases in temperature (during burial), and changes in environmental conditions such as humidity. Studies show that these parameters can cause initially formed minerals to break down to other Mg-carbonates releasing the water held within the mineral lattice (Morgan et al., 2015). While it is unlikely that $CO_2$ will be released by these breakdown mechanisms further research into the formation and stability of Mg-carbonates is required. In addition, atmospheric conditions also affect Mg-carbonate stability, thus should be considered to map suitable environmental conditions for industrial carbonation and storage solutions (Morgan et al., 2015).

### 15.2.3 Uptake

Uptake is limited and there is only demonstration-scale technology available for mineral carbonation at present. There is no current emissions reduction fund (ERF) method of issuance for Australian carbon credit units (ACCUs) related to mineral carbonation which potentially has inhibited development of this technology.

## 15.3 Sequestration potential

| Estimate of sequestration | Sequestration (Mt/yr) | Key evidence |
|---|---|---|
| **Technical Potential** | 1.1-4.5 Gt Globally | Bullock et al (2021) |
| **Economic potential by 2025** | No estimate | |
| **Economic potential by 2035** | No estimate | |
| **Economic potential by 2050** | 36 total, 16 Ni mining, 16 Au mining. | Bullock et al (2021), large uncertainties are noted. |

**Table 15-1: Best estimate of mineral carbonation potential. There are no estimates for enhanced weathering in Australia.**

The conversion degree of $CO_2$ ($E_{CO2}$) varies for different rocks. A summary by Sanna et al., 2014 reports that $E_{CO2}$ is 26–90% for serpentine, 8-90% for olivine, 75-80% for wollastonite, and 70-98% for brine. A pilot test by Snæbjörnsdóttir et al. (2018, 2020) reported that a Carbfix pilot test showed 95% of the injected $CO_2$ could become a carbonate mineral in less than two years (Matter et al., 2016).

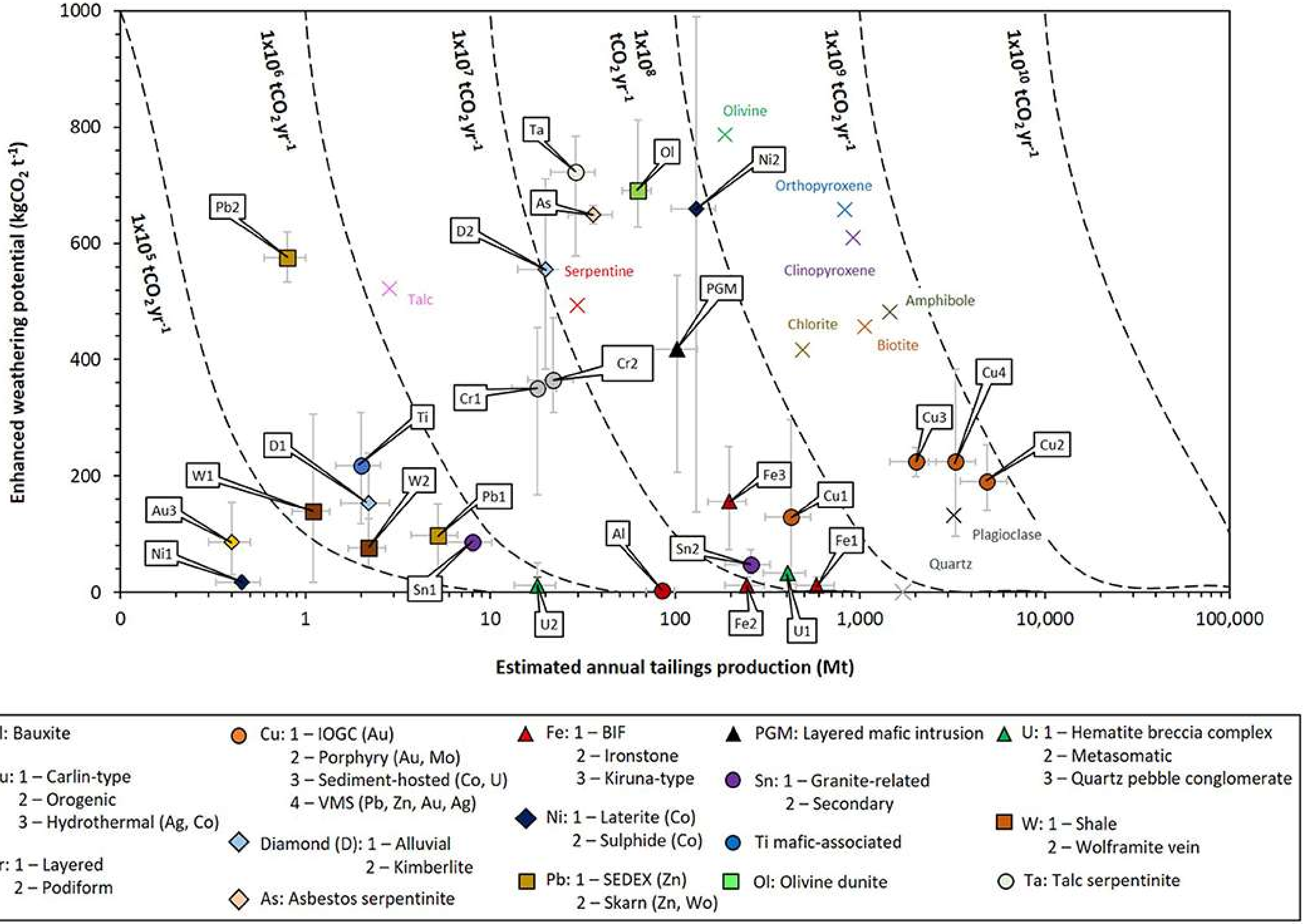



**Figure 15-4: $CO_2$ storage potential for different types of mine tailings globally. Nickel sulphide deposits, which dominate Australia's nickel production (Ni2) have the potential to sequester 100 Mt.yr$^{-1}$ but with the largest uncertainty of all deposit types due to variable geology (from Bullock et al., 2021).**

Bullock et al. (2021) suggests that orthomagmatic mafic and ultramafic rock-hosted and porphyry-Cu mining operations could capture 1.1-4.5 Gt $CO_2$ globally per annum, but uncertainty on estimates of carbon capture in these rocks is noted by the authors as substantial (Figure 15-4). In addition, the $CO_2$ capture rates is dependent on sequestration rates and realisation of this potential is unknown with the authors noting that only a fraction (3-20%) may be realised on timescales of less than 50 years.

## 15.3.1 Potential sequestration

Australia's large landmass and geology provides it with great potential to abate carbon through either mineral carbonation, or enhanced weathering processes. For either, sequestration potential should be calculated based on other, associated factors, such as those concerning $CO_2$ emissions through power generation, processing of materials (e.g., crushing and grinding) or transportation.

### Mineral Carbonation

In the near term, potential sequestration of carbon through mineral carbonation ex-situ could be explored at currently operating or closed mines, with suitable geology (e.g., mafic or ultramafic rocks) as waste rock or tailings. These are found around Australia and a complete inventory of volumes and mineralogy would be required to estimate the potential properly. Based on assumptions outlined below ex-situ mineralisation of tailings could sequester ~36 Mt/yr $CO_2$ if sufficient gas was available from diverted industrial emissions or direct air capture. BHP Nickel West's Mt Keith Mine is an example of an operating mine in Western Australia where studies of partial brucite carbonation in tailings showed current passive carbonation rates of 39,800 t/yr or 11% of the mine's emissions (e.g., Wilson et al., 2014;Figure 15-3, Employing methods to ensure all the brucite produced at Mt Keith Mine was carbonated would result in a factor of 100 improvement on the passive rate, 4 Mt/yr (or 10 times the mine's emissions; Power et al., 2013). Mt Keith Mine produces over 25% of Australia's Ni. Assuming similar carbonation rates for other mines, Ni mining could sequester 16 Mt/yr of $CO_2$ in tailings. Waste rock to tailings ratios are commonly ~5 for open cut mines such as Mt Keith. The composition of this rock is unknown but assuming it can consume 5% of the $CO_2$ that can be stored in the brucite fraction of the tailings this could add another 4 Mt/yr. This estimate concurs with estimates from Bullock et al. (2021) who estimate Ni sulphide, the primary type of Ni deposit mined in Australia, could sequester ~100 $MtCO_2$/yr globally. Comparing Australian production (160 kt Ni in 2021) to global production and allowing for countries where Ni is predominantly produced from Ni laterite (not hosted in favourable ultramafic rocks) Australia conservatively produces ~16% of the world's Ni sulphide ore, therefore tailings could be used to drawdown 16Mt $CO_2$/yr bsed on Bullock et al's (2021) global estimates, although Bullock et al. (2021; Figure 3) put large uncertainties on the CO2 drawdown potential of Ni sulphide deposits.

Nickel is not the only commodity that occurs in mafic and ultramafic rocks. Many of the gold (Au) mines in, particularly, Western Australia are hosted in mafic rocks (Figure 15-3). Australia's Au production in 2021 was 330 t Au (USGS, 2022). Assuming a grade of 2 g Au per tonne or mined rock, this would have resulted in ~165 Mt mafic tailings. The $CO_2$ sequestration potential of this rock is unknown because the Mg-silicates in the mafic tailings are much less reactive than in the ultramafic Ni tailings. Therefore, more research is required to produce a practical way of carbonating these minerals in an industrial setting. However, assuming 10t of tailings can be made to sequester 1t of $CO_2$ (25% of the capacity of Ni tailings), there is potential to mineralise another 16 Mt $CO_2$ in Au tailings. At the historic Woodsreef Asbestos Mine site in the Great Serpentinite Belt of NSW, extensive carbonate-rich crusts have formed naturally by recessive weathering of fine-grained material on the surface of the tailings pile (Figure 15-3). Oskierski et al. (2013)

reported that 1,400 to 70,000 t of $CO_2$ were sequestered within a period of 29 years after the mine was closed in 1983, suggesting a carbonation rate of 27 – 1330 g C/($m^2$·y). This rate is significantly higher than background rates of $CO_2$ uptake by chemical weathering. Efforts to accelerate the mineral carbonation at this mine site were conducted by various researchers. For example, McCutcheon et al. (2017) conducted a microbial mineral carbonation trial in which two pilots (0.5 $m^3$) on the tailings pile were treated with sulfuric acid. They found the degree of mineral carbonation was limited compared to previous experiments in laboratory settings. Hamilton et al. (2020) further investigated various treatment technologies (e.g., direct reaction with synthetic flue gas from power generation and repeated heating leaching with dilute sulfuric acid) to accelerate mineral carbonation using ultramafic tailings sampled from the mine.

### Enhanced weathering

Enhanced weathering has received little attention in Australia with many arid and semi-arid regions unsuitable due to low rates of weathering. Fine-grain basaltic material (dust or soil) can sequester carbon through natural weathering of basaltic dust applied to croplands (Goll et al. 2021). Weathering rates are increased through the reduction of grainsize of mafic or ultramafic material through crushing and griding. Production of basaltic soil or dust stocks through this process can be applied to pasture or crop lands in areas close to their source where they can have the positive effects of addition of nutrients in addition to sequestering $CO_2$ (Rinder and von Hagke, 2021). However, upscaling of $CO_2$ removal through way of distribution of basalt over soils may require increased mining of basaltic material, crushing and transportation which all need to be taken into account when assessing production, as opposed to mitigation of $CO_2$ (Goll et al., 2021). No estimates of potential sequestration exist for Australia but Beerling et al. (2020) estimate that the USA could remove up to 0.6 Gt $CO_2$/yr by enhanced weathering across the total land area used for agriculture. This estimate includes energy to crust and mill the basalt based on energy sources designed to limit global temperature rise to 2°C and transport to the croplands which would need to specifically be modelled for Australia.

## 15.4 Technology Readiness Potential and Commercial Readiness

It is difficult to assess the Technology Readiness Level of mineral carbonation Industries due to the lack of data linked to the limited pilot studies that have been undertaken. However, Mineral Carbonation International are currently building a mineral carbonation plant, suggesting they are progressing towards TRL7 (MCi website, 2022). Internationally, Carbfix (an academic-industrial partnership) has developed a novel approach of mineral carbonation for capturing and storing $CO_2$ by its capture in water and its injection into subsurface basalts (Snæbjörnsdóttir et al., 2020; Carbfix website, 2022). Likewise, CarbMinLabs has developed out of a decade of research led by the University of British Columbia and is actively completely field trials for implementation of mineral carbonisation at mine sites (CarMinLabs website, 2022).

In Australia examples of mineral carbonation industries are limited. However, recently funding announcements to accelerate this technology have been made. For example:

- In early June 2022, Australian Commonwealth Government announced $412 million (AUD) of new investment (Minister Taylor's office, 2021) for carbon capture projects. Over the six already funded projects, two companies' projects are focusing on mineral carbonation:
    - Mineral Carbonation International – up to $14.6 million (AUD) towards the construction of a mobile demonstration plant that captures and uses $CO_2$ to produce manufacturing and construction materials, such as concrete, plasterboard and fire-retardant materials on Kooragang Island, New South Wales

- Boral Limited – up to $2.4 million (AUD) towards a pilot scale carbon capture and use project to improve the quality of recycled concrete, masonry and steel slag aggregates at New Berrima, New South Wales.

Alcoa's Kwinana aluminium refinery in Western Australia applied mineral carbonation at an industrial scale (Alcoa, 2012; Azadi et al. 2019), with suggestions that it could sequester 300,000 tonnes $CO_2$ per annum (ReliablePlant, 2007; World Aluminium, 2004). Focusing on bauxite residue treatment, the carbonation involves the addition of carbon dioxide ($CO_2$) to thickened residue slurry to lower the pH of the residue, from pH 13 to a pH of less than 10.5, similar to natural alkalinity in soils.

In late June 2022, the WA state government announced the commencement of the for integrated mineral carbonation in WA Roadmap for integrated mineral carbonation in WA (Hon Bill Johnston MLA Minister's office, 2022). This will be completed by Curtin University, managed by MRIWA and involves the GSWA developing models for carbon capture and mineral carbonation capacity.

In terms of mineral carbonation landscape in Australia companies that are moving forward on this appear to be BHP, MCI, Boral (in concrete, etc). BHP's activities on ex-situ mineral carbonation using mine waste materials at Mt Keith are recently reported by Australia Financial Review (Ker and Phan, 2022).

In addition, CSIRO has recently launched a Permanent Carbon Locking Future Science Platform (CarbonLock FSP, 2022; Dawkins, 2022) which will harness biology, chemistry and engineering to drive innovation in carbon capture and carbon storage science. In addition, CSIRO Mineral Resources and the CarbonLock FSP are organising a cutting-edge symposium on *Locking Carbon in Minerals* which will be hold in Perth, WA, in 19 - 23 June 2023.

Those investment and initiatives indicate the future potential of mineral carbonation capacity from technique achievable to policy feasible.

#### Costs

Studies outlining current costs of engineered carbon storage using CCS technology suggest that they can vary between 28 and 300 $/t (Hitch and Dipple, 2012; Khoo et al., 2011; Mazzotti et al., 2005; Penner et al., 2004; Sanna et al., 2014; Li et al., 2018). From an economic point of view, the cost shows the potential of mineral carbonation to compete with the geological storage methods, the cost of which varies between 5 and 160 $/t (Irlam, 2017; Rubin et al., 2015; Schmelz et al., 2020). The costs of mineral carbonation may be further reduced into the future with alternative energy solutions, new technologies and operating procedures.

## 15.5 Social, environmental impacts, risks, and co-benefits

### 15.5.1 Impacts and risks

In-situ mineral carbonation requires injecting $CO_2$ into the subsurface rock. Since many of the reactions that sequester the $CO_2$ result in clogging of the fluid flow pathways in rock it may be necessary to create further permeability by inducing fracturing. Detailed understanding of the geology and careful, ongoing monitoring will be required to mitigate both perceived and actual risk. For enhanced weathering, it is necessary to understand the mineralogy and trace metal content of the material being used to prevent toxic forms of minerals or trace elements being spread over agricultural land.

### 15.5.2 Co-benefits

Enhanced weathering can improve agricultural productivity through a number of mechanisms including increasing nutrient levels, moderating soil acidity and increasing organic material. It can also ppotentailly improve water retention in the soil (Goll et al., 2021 and references therein).

Tailings are commonly stored in dams with fine-grained material being stored mixed with water. Dam failures can present a major risk in mining areas and major efforts are being made to develop new methods to stabilise the tailings. Experiments show that carbonation of brucite increases the strength of tailings material and can therefore reduce the risk of dam failure. Carbonation of asbestiform minerals from legacy mines, such as the Woodsreef Asbestos mine in NSW, also presents a way to contain potentially harmful, naturally occurring material.

Another potential co-benefit is the production of useful materials. In some cases these can partially displace carbon intensive products such as cement, leading to additional CO2 benefits (Benhelal et a,l 2018).

## 15.6 Barriers to implementation

Mineral carbonation technologies are currently at a relatively low TRL and still in scale-up and pilot phases for the most advanced options. Therefore, substantial investment is required to advance these technologies to full industrial scale implementation. There has been little social or financial incentive for many mining companies, who are well positioned to implement mineral carbonation at their active sites. This may be because these mines are often remote and there is currently no ERF method for mineral carbonation. However, evolving ESG sentiment among investors at all levels in the sector is likely to drive investment in mineral carbonation technologies for emissions that cannot be eliminated by using alternative energy sources e.g. electrification.

## 15.7 Scaling knowledge gaps:

Further research is required to assess the potential for sequestration of carbon through carbon mineralisation. The maturity of the research is variable (e.g. IEAHG, 2022), but not adequate to make valued judgements on storage capacities, rates of mineral carbonation reactions in an industrial setting, or practicability of mineral carbonation in Australia. The main challenge of mineral carbonation is that it is slow, whether performed in-situ or on extracted mine tailings and other waste material. Fundamental research is required to understand not only the most significant influencing factors on carbonation rates but also for technical implementation in both tailings and in-situ.

1. How do we accelerate carbonation reactions in industrial settings?
    a. Particle Size - limiting capacity and reaction kinetics of carbonation as functions of particle size distribution – while many claim to examine particle size effect (e.g. Assima et al., 2013), this is often done superficially or only considering larger sizes.
    b. Electrochemical methods to increase $CO_2$ solubility - developing new pathways using solar thermal and renewable energy to produce alkaline ions by electrochemical methods could increase $CO_2$ solubility in water and increase carbonation rates.
    c. Simulation and modelling of predicted $CO_2$ sinks - experiments can be coupled with molecular simulation for the study of mineral carbonation mechanisms to determine more efficient carbon storage. Reactive transport modelling to investigate the rate of mineral carbonation

with different kinetics models could provide a way to assess their impact in $CO_2$ geo-sequestration.

d. Biological and inorganic catalysts - Determination of appropriate catalysts for mineral carbonation including their dependence on local rock and fluid chemistry and sequestration substrate.

2. What infrastructure developments need to be made to efficiently integrate mineral carbonation into mining operations?

   a. New methods are required to integrate mineral carbonation with tailings/waste management options at active mafic-ultramafic mine tailings sites. Studies are required to assess the benefits and challenges of various technical routes to integrate mineral carbonation into tailings/waste management including the following:

      i. Measuring baseline rates of passive carbonation processes at tailing storage facilities

      ii. Determining ex-situ carbonation routes using fresh tailings building on knowledge from the fundamental studies of reaction kinetics and catalytic enhancement outlined above.

      iii. Understanding pre-treatment options of tailings materials for increasing the capacity and reaction rate of $CO_2$ mineralisation e.g., extracting highly reactive brucite from less reactive serpentine prior to carbonation, or strategies for enhancing permeability in tailings (Bullock et al. 2021)

      iv. Engineering solutions to treat existing and new tailings produced through mining mafic-ultramafic hosted ore bodies

3. Where are the most appropriate places to employ enhanced weathering mineral carbonation and what are the contributions from biotic and abiotic weathering process?

   a. Goll et al. (2021) showed that the amount of $CO_2$ removal that occurs is highly variable across Australia. They also illustrate through modelling of the biotic and abiotic effects of adding basalt dust to ecosystems that the improvement in soil fertility achieved enhances ecosystem carbon storage, suggesting that global $CO_2$ removal through enhanced weathering mineral carbonation is larger than previously suggested. More detailed, site specific work through different forestry and agricultural regions of Australia is required to understand the magnitude of this opportunity.

4. What are the most appropriate engineering solutions for in-situ mineral carbonation?

   a. Even though this is not a new area of research (Oelkers et al., 2008) appropriate mineral carbonation formation processes and assessment of knowledge gaps in mineral carbonation studies is necessary in order to design experiments that will be applicable to real world examples. As demonstrated in earlier studies (e.g., Gysi and Stefánsson, 2011; 2012; Rosenbauer et al., 2012), it will be necessary to develop a series of geochemical experimental designs informed by numerical modelling, to determine conditions necessary to ensure long-term stability of industrially produced Mg-carbonates.

   b. In addition, a preliminary assessment of the technical process of in-situ mineral carbonation based on selected sites, for assessing $CO_2$ flows for carbonation processes in underground rocks is required. Such analyses would improve the accuracy of assessing in-situ mineral carbonation potential in Australia. This will enable a preliminary design of a $CO_2$ injection system based on existing pilot test systems, e.g. reportedly a Carbfix pilot test showed 95% of the injected $CO_2$ at their test site could become a carbonate mineral in less than two years (Snæbjörnsdóttir et al. 2018, 2020; Matter et al., 2016).

c. This model could be complemented by geochemical modelling of $CO_2$-brine-rock interactions for selected rock types and conditions to understand the impact of geochemical reactions on mineralogy, brine composition, and rock porosity that result from $CO_2$ injection (Rosenbauer et al., 2012).

5. Where are the best places to carry out in-situ mineral carbonation?

   a. To establish the feasibility of mineral carbonation and assess potential volumes of storage, identification and ranking of possible in-situ carbonation sinks on the Australian continent may be beneficial. To do this mineral carbonation potential mapping is required.

   b. For example, if carbonation of *in-situ* rock can be achieved through pumping $CO_2$ into serpentinised ultramafic rocks in order to map the carbonation potential and therefore conventional geological storage of $CO_2$ we first need to map the distribution of ultramafic rocks in uncovered and covered regions of Australia. Although, this is largely completed in 2D (Hoatson et al., 2009a,b ) this is not completed in 3D, thus estimation of rock volumes is not achievable.

   c. Publicly available magnetic and gravity data may be used to determine the depth and dip (3D) of these rock bodies, however they will not determine the presence of amenable mineralogy and/or presence of porosity and permeability within them. Nevertheless, determining their volume could indicate potential targets for further work and provide an estimate of the volume of 'potential' carbonation sinks (for example, Cutts et al., 2020; Mitchinson et al., 2020).

6. What key research is required to unlock potential for mineral carbonation to produce commercially viable products?

   a. Carbonate minerals are used in a number of industrial applications, including production of cement, paint filler, as an acid reducing agent, some fertilisers and paint fillers (Woodall et al., 2019). However, some of these products also release $CO_2$ into the atmosphere or require high input of electricity to produce, so are not currently ideal for mineral carbonation, or may require carbonated rock aggregate to be transported long distances from its production site. Research into processes that can use mineral carbonation products for industrial application without emitting large amounts of $CO_2$ during the process, or subsequently is required.

   b. Reduction of particle size for mineral carbonation may require crushing and grinding – a process that use and can emit $CO_2$. Research into crushing and grinding vessels and methods may be required to help reduce the $CO_2$ emissions caused by this process.

## 15.8 Chapter References


Assima, G.N., Larachi, F., Molson, J., & Beaudoin, G. (2013) Dynamics of carbon dioxide uptake in chrysotile mining residues – Effect of mineralogy and liquid saturation. Int. J. Greenh. Gas Control, 12, 124–135 doi: 10.1016/j.ijggc.2012.10.001

Azadi, M., Edraki, M., Farhang, F. and Ahn, J., 2019. Opportunities for Mineral Carbonation in Australia's Mining Industry. Sustainability, 11(5).

Bea, S.A. et al., 2012. Reactive Transport Modeling of Natural Carbon Sequestration in Ultramafic Mine Tailings. Vadose Zone Journal, 11(2).

Beerling, D.J., Kantzas, E.P., Lomas, M.R. et al., 2020, Potential for large-scale CO2 removal via enhanced rock weathering with croplands. Nature 583, 242–248 https://doi.org/10.1038/s41586-020-2448-9

Benhelal, E. et al., 2018. “ACEME”: Synthesis and characterization of reactive silica residues from two stage mineral carbonation Process. Environmental Progress & Sustainable Energy, 38(3).

Bullock, L.A., James, R.H., Matter, J., Renforth, P., and Teagle, D.A.H., 2021. Global Carbon Dioxide Removal Potential of Waste Materials From Metal and Diamond Mining. Frontiers in Climate, doi.org/10.3389/fclim.2021.694175

Carbfix Website <https://www.carbfix.com/> [accessed July, 2022].

CarbMinLab, Optimizing CO2 sequestration in industrial waste. Website <https://carbmin.ca/> [accessed July, 2022].

CarbonLock FSP, CSIRO, website <https://research.csiro.au/carbonlock/>, [accessed July, 2022].

Cutts, J. A., Dipple, G. M., Hart, C., & Milidragovic, D. (2020). Assessment of the carbon mineralization potential of British Columbia by quantifying the response of physical properties to the alteration of ultramafic rocks. In Geoscience BC Summary of Activities 2019; Minerals, Geoscience BC, Report, 01, 137–144.

Dawkins, R., 2022, Locking away carbon permanently, Resourceful magazine, ISSUE 26: SUSTAINABLE RESOURCES

Goll, D.S., Ciais, P., Amann, T., Buermann, W., chang, J., Eker, S., Hartmann, J., Janssens, I., Li, W., Obersteiner, M., Penuelas, J., Tanaka, K., Vicca, S., 2021. Potential Co2 removal from enhanced weathering by ecosystem responses to powdered rock. Nature Geoscience, 14, 545-549, https://doi.org/10.1038/s41561-021-00798-x

Gysi, A.P. and Stefánsson, A. (2011) CO2–water–basalt interaction. Numerical simulation of low temperature CO2 sequestration into basalts. Geochimica et Cosmochimica Acta 75, 4728-4751.

Gysi, A.P. and Stefánsson, A. (2012) CO2-water–basalt interaction. Low temperature experiments and implications for CO2 sequestration into basalts. Geochimica et Cosmochimica Acta 81, 129-152.

Harrison, A.L., Power, I.M., Dipple, G.M., 2013, Accelerated carbonation of brucite in mine tailings for carbon sequestration. Environ. Sci. Technol., 47: 126-134

Hitch, M. and Dipple, G.M., 2012. Economic feasibility and sensitivity analysis of integrating industrial scale mineral carbonation into mining operations. Minerals Engineering, 39: 268-275.

Hoatson, D.M., Jaireth, S., Whitaker, A.J., Champion, D.C., Claoue-Long, J.C. 2009. Guide to Using the Australian Archean Mafic-Ultramafic Magmatic Events Map. Record 2009/041. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/69935

Hoatson, D.M., Jaireth, S., Whitaker, A.J., Champion, D.C., Claoue-Long, J.C. 2009. Archean Mafic-Ultramafic Magmatic Events Resource Package. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/69347

Hon Bill Johnston MLA Minister's office, 2022, Roadmap for integrated mineral carbonation in WA, < https://www.mediastatements.wa.gov.au/Pages/McGowan/2022/06/Roadmap-for-integrated-mineral-carbonation.aspx >, [accessed July, 2022].

Hosseini, T., Haque, N., Selomulya, C. and Zhang, L., 2016. Mineral carbonation of Victorian brown coal fly ash using regenerative ammonium chloride – Process simulation and techno-economic analysis. Applied Energy, 175: 54-68.

IEAGHG, 2022. Mineral Carbonation using Mine Tailings – A Strategic Overview of Potential and Opportunities, 2022-10.

Irlam, L., 2017. Global costs of carbon capture and storage. Global CCS institute, 16.

Kelemen, P.B., McQueen, N., Wilcox, J., Renforth, P., Dipple, G. and Vankeuren, A.P. (2020) Engineered carbon mineralisation in ultramafic rocks for CO2 removal from air: Review and new insights. Chemical Geology 550, 119628.

Ker, P., and Phan, L., 2022, The sludge that could save BHP’s carbon footprint, Australia Financial Review

Khoo, H.H. et al., 2011. Carbon Capture and Mineralization in Singapore: Preliminary Environmental Impacts and Costs via LCA. Industrial & Engineering Chemistry Research, 50(19): 11350-11357.

Li, J., Hitch, M., Power, I., Pan, Y., 2018. Integrated Mineral Carbonation of Ultramafic Mine Deposits—A Review. Minerals 2018, 8, 147.

Matter, J.M., Stute, S., Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Gislason, S.R., Aradottir, E.S., Sigfusson, B., Gunnarsson, I., Sigurdardottir, H., Augsson, E., Axelsson, G., Alfredsson, H.A., Wolff-Boenisch, D., Mesfin, K., Taya, D.F., Hall, J., Dideriksen, K., and Broecker, W.S., 2016. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. Science, 352 (6291): 1312-1314.

Mazzotti, M. et al., 2005. Mineral carbonation and industrial uses of carbon dioxide, IPCC special report on carbon dioxide capture and storage. Cambridge University Press.

McCutcheon, J., Turvey, C., Wilson, S., Hamilton, J. and Southam, G., 2017. Experimental Deployment of Microbial Mineral Carbonation at an Asbestos Mine: Potential Applications to Carbon Storage and Tailings Stabilization. Minerals, 7(10).

McGrail, B.P., Schaef, H.T., Ho, A.M., Chien, Y-J., Dooley, J.J., Davidson, C.L., 2006, Potential for carbon dioxide sequestration in flood basalts, Journal of Geophysical Research, v. 111, B12201, doi:10.1029/2005JB004169

Mineral Carbonation International (MCi). Mineral Carbonation International (MCi) website <https://www.mineralcarbonation.com/customers> [accessed July, 2022].

Minister Taylor's office, 2021, $412 million of new investment in carbon capture projects, website < https://www.minister.industry.gov.au/ministers/taylor/media-releases/412-million-new-investment-carbon-capture-projects >, [accessed July, 2022].

Mitchinson, D., Cutts, J., Fournier, D., Naylor, A., Dipple, G., Hart, C. J. R., Turvey, C., Rahimi, M., & Milidragovic, D. (2020). The carbon mineralization potential of ultramafic rocks in British Columbia: a preliminary assessment. Geoscience BC Report 2020-15/MDRU Publication 452, 25.

Morgan B, Siobhan, W, Madsen, I, Gozukara, Y, Habsuda, J, 2015, Increased thermal stability of nesquehonite (MgCO3.3H2O) in the presence of humidity and CO2: implications for low temperature CO2 storage, International Journal of Greenhouse Gas Control, v 39, p. 366-376

Oelkers, E.H., Gislason, S.R. and Matter, J. (2008) Mineral carbonation of CO2. Elements 4, 333-337.

Oskierski, H.C., Dlugogorski, B.Z. and Jacobsen, G., 2013. Sequestration of atmospheric CO2 in chrysotile mine tailings of the Woodsreef Asbestos Mine, Australia: Quantitative mineralogy, isotopic fingerprinting and carbonation rates. Chemical Geology, 358: 156-169.

Penner, L.R., O'Connor, W.K., Dahlin, D.C., Gerdemann, S.J. and Rush, G.E., 2004. Mineral carbonation: energy costs of pre-treatment options and insights gained from flow loop reaction studies, Albany Research Center (ARC), Albany, OR (United States).

Power, I.M., Harrison, A.L., Dipple, G.M., Wilson, S.A., Keleman, P.B., Hitch, M., Southam, G., 2013. Carbon Mineralisation: From Natural Analogue to Engineered Systems, Reviews in Mineralogy & Geochemistry, v.77, p. 305-360.

Power, I. et al., 2014. Strategizing Carbon-Neutral Mines: A Case for Pilot Projects. Minerals, 4(2): 399-436.

Power, I.M. et al., 2011. Microbially mediated mineral carbonation: roles of phototrophy and heterotrophy. Environ Sci Technol, 45(20): 9061-8.

Power, I.M. et al., 2021. Carbonation, Cementation, and Stabilization of Ultramafic Mine Tailings. Environ Sci Technol, 55(14): 10056-66. https://doi.org/10.1021/acs.est.1c01570

RP news wires, Noria Corporation, Alcoa launches Carbon Capture technology for refineries, < https://www.reliableplant.com/Read/6316/alcoa-launches-carbon-capture-technology-for-refineries- >

Raymond, O.L. (editor), Gallagher, R., (editor), Shaw, R., Yeates, A.N., Doutch, H.F., Palfreyman, W.D., Blake, D.H., Highet, L., 2012, Surface Geology of Australia 1:2.5million scale dataset 2012 edition, http://dx.doi.org/10.26186/5c636e559cbe1

Rinder, T., and von Hagke, C., 2021. The influence of particle size on the potential of enhanced basalt weathering for carbon dioxide removal – Insights from an regional assessment. Journal of Cleaner Production, 315: 128178

Rashid, M.I. et al., 2018. ACEME: Direct Aqueous Mineral Carbonation of Dunite Rock. Environmental Progress & Sustainable Energy, 38(3).

Rosenbauer, R.J., Thomas, B., Bischoff, J.L. and Palandri, J. (2012) Carbon sequestration via reaction with basaltic rocks: Geochemical modeling and experimental results. Geochimica et Cosmochimica Acta 89, 116-133.

Rubin, E.S., Davison, J.E. and Herzog, H.J., 2015. The cost of CO2 capture and storage. International Journal of Greenhouse Gas Control, 40: 378-400.

Sanna, A., Uibu, M., Caramanna, G., Kuusik, R. and Maroto-Valer, M.M., 2014. A review of mineral carbonation technologies to sequester CO2. Chem Soc Rev, 43(23): 8049-80.

Schmelz, W.J., Hochman, G. and Miller, K.G., 2020. Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States. Interface Focus, 10(5): 20190065.

Snæbjörnsdóttir, S.Ó., Gislason, S.R., Galeczka, I.M. and Oelkers, E.H. (2018) Reaction path modelling of in-situ mineralisation of CO2 at the CarbFix site at Hellisheidi, SW-Iceland. Geochimica et Cosmochimica Acta 220, 348-366.

Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S.R. and Oelkers, E.H. (2020) Carbon dioxide storage through mineral carbonation. Nature Reviews Earth & Environment 1, 90-102.

Southam, G. et al., 2020. Accelerating Mineral Carbonation in Ultramafic Mine Tailings via Direct CO2 Reaction and Heap Leaching with Potential for Base Metal Enrichment and Recovery. Economic Geology, 115(2): 303-323.

Ukwattage, N.L., Ranjith, P.G., Yellishetty, M., Bui, H.H. and Xu, T., 2015. A laboratory-scale study of the aqueous mineral carbonation of coal fly ash for CO2 sequestration. Journal of Cleaner Production, 103: 665-674.

Voigt, M., Mareine, C., Baldermann, A., Galeczka, I.M., Wolff-Boenisch, D., Oelkers, E.H., Gislason, S.R., 2001, An experimental study of basalt–seawater–CO2 interaction at 130 °C. Geochimica et Cosmochimica Acta 308, 21-41. https://doi.org/10.1016/j.gca.2021.05.056

Wilson, S.A., Dipple, G.M., Power, I.M., Thom, J.M., Anderson, R.G., Raudsepp, M., Gabites, J.E., Southam, G., 2009. Carbon Dioxide Fixation within Mine Wastes of Ultramafic Hosted Ore Deposits: Examples from the Clinton Creek and Cassiar Chrysotile Deposits, Canada. Economic Geology 104, 95-112. https://doi.org/10.2113/gsecongeo.104.1.95

Wilson, S.A., Harrison, A.L., Dipple, G.M., Power, I.M., Barker, S.L., Mayer, U.K., Fallond, S.J., Raudsepp, M., Southam, G., 2014. Offsetting of CO2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining. International Journal of Greenhouse Gas Control. 25: 121-140.

Woodall, C.M., McQueen, N., Pilorgé, H., Wilcox, J., 2019. Utilization of mineral carbonation products: current state and potential. Greenhouse Gases: Science and Technology. 9(6): 1096-1113.

World Aluminium, 2004, Bauxite Residue Managemetn: Best Practise, European Alumium Association, 32p. Bauxite_Residue_Management_-_Best_Practice_(IAI).pdf (aluminium.org.au)

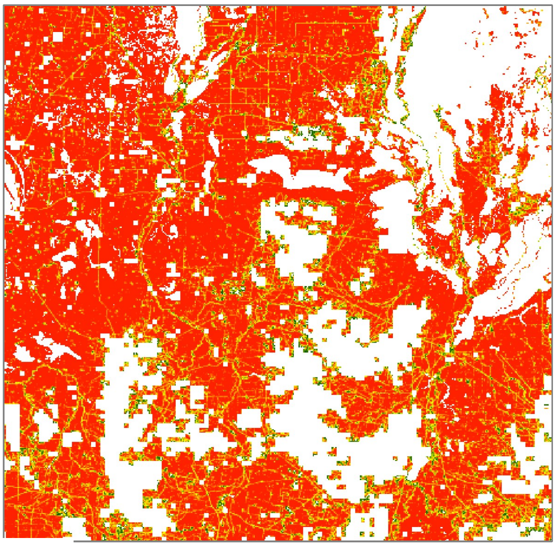
# Appendix

## Appendix for chapter 5: Plantation and farm forestry

Because of the rainfall-based project size limits specified by the Farm Forestry methodology, a further filtering of the potential extent of project activity was applied to represent this constraint. This was important, as the project size limits have the potential to impact the financial viability through reducing the opportunities of reducing costs by economies of scale (i.e., fixed project costs are relatively more constraining in small compared with large projects.

Two steps were taken to build the project size constraint into the analysis. First, a moving window filter was applied, whereby cells were scanned in sequential order. For each target cell an area equal to 1.5x the allowed limit (i.e. 1.5 x 100ha = 150ha, or 1.5 x 300ha = 450ha, depending on rainfall) was scanned around each target cell, and if the feasible area within that window was greater than or equal to that allowed under current rainfall (defined as the rainfall of the target cells), then cells were selected up to, but not exceeding, the allowed area limit. Although grid cells in the feasible mask are at 250m x 250m resolution, they have values that represent the eligible areas within each grid. Cell selection for inclusion in the analysis was then determined by ranking all cells within the scanned area in decreasing order of viable area, and then aggregating cells until the limit was reached. Once a cell was selected for inclusion, it was flagged as being unavailable for future selection. This resulted in a patchwork of contiguous 'potential projects' of the correct spatial extent (Figure A1b).

The second constraint that was applied is that no more than 30% of a property can be included as part of a project. To apply this constraint the average property areas at the scale of Statistical Local Area 4.0 regions were obtained from the Agricultural Commodities, Australia, 2017-18 database (https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02017-18?OpenDocument), and the probability of project inclusion calculated as the number of potential projects within each SA4 region, divided by the average property size (Figure 4.11.2c). Although this is an approximation of the areal constraints embedded within the methodology, without detailed information on property sizes, it provides an initial indication of the potential area (and sequestration) available under the method. A Monte Carlo approach was then used in the economic analyses, with 1000 replicated analyses, where for each replicate potential projects were selected for inclusion based on the appropriate SA4-level probability of inclusion.



(b) (c)

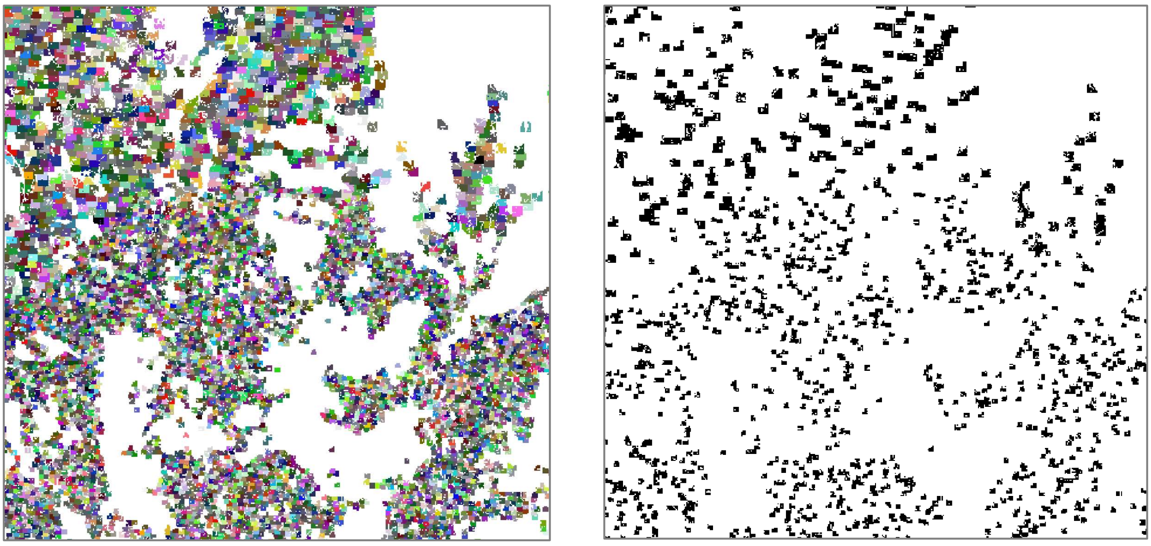


**Figure A1.** (a) Initial eligibility layer. (b) Potential project extents of 100ha (bottom half) and 300ha (top half), spanning the 400mm rainfall boundary, prior to filtering by average property area. (c) Potential project extents after filtering to account for property area constraints.

# Shortened forms

| | |
|---|---|
| ACCU | Australian Carbon Credit Unit |
| AET – | Avoided Emission Technologies |
| AEST | Avoided Emission and Storage Technologies |
| ANZBIG | The Australian and New Zealand Biochar Industry Group |
| CCUS | Carbon Capture Utilisation (Use) and Storage |
| CDR – | Carbon Dioxide Removal |
| CER – | Clean Energy Regulator |
| CRL | Commercial Readiness Level |
| DISER | Department of Industry, Science, Energy and Resources |
| ERF | Emission Reduction Fund |
| FullCAM – | Full Carbon Accounting model |
| GHG | Greenhouse Gas |
| HIR | Human induced regeneration |
| IBI | International biochar initiative |
| ICORA | International Carbon Reduction and Offset Alliance |
| LETS | Low Emission Technology Strategy |
| MACCS | Marginal abatement cost curves |
| Mta | Million tonnes annually |
| NFfMR | Native forest from managed regrowth |
| NETS | Negative emission Technology Systems |
| NPC | Net Present Cost |
| NPV | Net Present Value |
| NRM | Natural Resource Management |
| NVIS | National Vegetation Inventory System |
| PBS | Pyroloysis Biochar Systems |
| PyCSS | Pyrolytic Carbon capture and Storage |
| SDG's | Sustainable Development Goals |
| VCE | Vegetated coastal ecosystems |

# Glossary

| Term | Definition |
|---|---|
| **Avoided Emissions** | Avoided emissions refer to deliberate activities that aim to prevent carbon from being released into the atmosphere. |
| **Avoided emission technologies** | Technologies and approaches that avoid emissions |
| **Carbon dioxide removal** | Refers to approaches that take advantage of natural biological systems to take up and store atmospheric carbon dioxide. Examples include afforestation/reforestation, soil carbon and blue carbon. This also referred as Natural, Nature-Based or Natural-Climate Solutions |
| **Engineered Solutions** | Refers to approaches that rely on chemistry to capture and store atmospheric carbon dioxide. Examples includer mineral carbonation, and ocean alkalinity addition. In many cases these solutions involve combining two different capture and storage technologies such as Direct Air Capture (DAC) and Carbon Capture and Storage (CCS). |
| **Economic sequestration** | the maximum technically or biophysically possible sequestration within the definition of the technical option reviewed. |
| **Hybrid Solutions** | Approaches that combine biological capture and geological storage. Examples of this include BioEnergy Carbon Capture and Storage (BECCS) which involves using Biomass to capture carbon. |
| **Length of sequestration** | The likely longevity of sequestration |
| **Negative Emissions** | Sometimes known as Carbon Dioxide Removal (CDR), remove carbon dioxide ($CO_2$) from the atmosphere with the intent of reducing the atmospheric greenhouse gas (GHG) concentrations |
| **Negative Emission Technologies** | Negative emissions are delivered via one of more enabling technologies which can capture and store $CO_2$, away from the atmosphere, often termed Negative Emissions Technologies (NETs). NETs remove $CO_2$ from the atmosphere via biological (photosynthetic) or chemical pathways. |
| **Offsets (ERF)** | An emissions offset is a reduction in emissions made in order to compensate for (or offset) an emission made elsewhere. |

| | |
|---|---|
| **Technical sequestration** | Economic sequestration is the quantity of sequestration attainable given concerted efforts to implement the necessary technical and management changes. |
| **Realisable sequestration** | Realisable sequestration is that sequestration that considers the limitations of resource constraints, implementation feedbacks that can limit scaling, appropriate institutional settings and incentives and removal of barriers |
| **Scalability** | The potential to increase the uptake of a technology and the corresponding increase of carbon sequestration or negative emissions. |

**As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.**

CSIRO. Unlocking a better future for everyone.

**Contact us**

1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

**For further information**

Peter Fitch
+61 2 6216 7017
peter.fitch@csiro.au

Michael Battaglia
+61 3 6237 5612
michael.battaglia@csiro.au

Andrew Lenton
+61 3 6232 5472
andrew.lenton@csiro.au