CSIRO IMPACT SCIENCE
www.csiro.au

Potential for Australian land-sector carbon sequestration and implications for land use, food, water and biodiversity

Report for the Australian National Outlook 2015

Brett A. Bryan, Steve Hatfield-Dodds, Martin Nolan, Lisa McKellar, Michael J. Grundy, Rebecca McCallum

Citation

Bryan BA, Hatfield-Dodds S, Nolan M, McKellar L, Grundy MJ, McCallum R (2015) *Potential for Australian land-sector carbon sequestration and implications for land use, food, water, and biodiversity: Report for the Australian National Outlook 2015*. CSIRO, Australia.

Copyright and disclaimer

Important disclaimer

Contents

Figures

Tables

Acknowledgments

The National Outlook project was funded by CSIRO, and delivered in collaboration with our University partners. We thank this report's reviewers: Professor Alan Randall (University of Sydney / Ohio State University, USA), Professor Neil Byron (University of Canberra), John Radcliffe (Honorary Research Fellow, CSIRO), Professor Matthias Ruth (Northeastern University, USA), Dr Neville Crossman, CSIRO and Dr Andrew Reeson, CSIRO. The authors would also like to acknowledge the contribution of Michelle Rodriguez who provided significant editorial input.

Executive summary

This report presents new analysis of the potential future supply of carbon credits from the 85 Mha intensive-use agricultural land of Australia. We find that agricultural land in Australia has significant potential to store carbon, and to mitigate and offset greenhouse gas emissions over coming decades.

We analyse potential for the supply of carbon credits from carbon plantings (non-harvest, fast-growing, single-species Eucalyptus plantations) as well as environmental plantings (bio-diverse mix of native species plantings designed to recreate local ecosystem composition, structure and function) under a range of global outlooks, levels of carbon payments for land sector sequestration, and market settings to support voluntary biodiversity conservation. The analysis was based on the Land Use Trade-Offs (LUTO) model of Australian land use futures—an integrated environmental-economic model of land use response over time to different combinations of key global, national, and local drivers. We explore inertia in the uptake of land use change using an uptake curve which assumes that land use changes over a sixteen year period from when the new land use becomes more profitable than current agricultural use, with half of the transition taking place after eight years. We provide sensitivity analysis of uptake and land use change using adoption hurdle rates which imposed profitability thresholds which must be exceeded before land use change occurs.

We find that carbon and environmental plantings have the technical potential to provide up to 11.3 Gt CO_2 to 13.2 Gt CO_2 in cumulative sequestration over the period to 2050 (depending on assumptions about land use change) with average annual abatement of up to 513 Mt CO_2 over the period 2031–2050. These findings assume payments per unit of carbon supplied that are broadly consistent with the carbon price trajectories in the medium and high scenarios modelled by The Treasury (2011) and by The Treasury and the Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education (DIICCSRTE) (2013). We also find strong threshold effects in the supply of carbon credits. The time profile of biophysical carbon sequestration and assumptions about uptake inertia together result in low volumes of credits being delivered prior to 2030, even with very high carbon payment rates.

We find that settings focused on carbon alone are not projected to generate substantial biodiversity benefits from Australia's agricultural land, but that market-based payments for carbon create opportunities for harnessing carbon incentives to achieve biodiversity co-benefits. Over most of the study area, the sequestration ability, and therefore the profitability of environmental plantings was far exceeded by the high-growth tree species typically used in carbon plantings. However, when complemented by policy settings that target the delivery of cost-effective biodiversity co-benefits, the area of environmental plantings was increased considerably.

Increasing food production and increasing carbon sequestration were not mutually exclusive, but food production in 2050 is highest in scenarios with no abatement incentives. Under very strong abatement incentives, livestock output peaks between 2020 and 2030 and then has the potential to fall slightly below current production levels. While outside the scope of the current study, over the long term, effective global action to reduce greenhouse emissions would limit climate impacts and increase agricultural output.

We also find that uptake of carbon and environmental plantings could result in significant reductions in surface water flows. Water interceptions by trees accounted for 25%–50% of total projected national water use in 2050 in the scenarios with strong or very strong abatement incentives. As an indication of the trade-offs involved, carbon and environmental plantings in Australia's water-limited catchments accounted for up to 22% of total interceptions, up to 10% of national water use, and up to 2.2 Gt CO_2 (22%) of cumulative national land-sector sequestration over the period to 2050.

These findings illustrate both the potential scale of changes in biodiversity, food production, and water resource availability associated with land use change, and the importance of the impacts and potential unintended consequences that could arise, particularly from governance arrangements that do not account for interactions across these different domains. The analysis and findings draw attention to the need to understand the interactions, synergies, and trade-offs that may occur.

This report closely complements two scientific papers of the *Australian National Outlook* – Bryan et al. (2014) and Bryan et al. (in review) – and makes two distinct contributions:

First, the report explores an additional approach to uptake dynamics. We do this by representing inertia in land-use change using an uptake curve which assumes that land use changes over a sixteen year period from when a new land use becomes more profitable than current agricultural use in a specific location, with half of the transition taking place after eight years. This is different from Bryan et al. (2014) and Bryan et al. (in review) which provided sensitivity analysis of uptake and land-use change using 'hurdle rates' that imposed profitability thresholds which must be exceeded before land-use change occurs – an approach well recognised in the literature for providing sensitivity analysis of potential outcomes under uncertain information. However, this approach does not explore other issues that can influence the rate of sectoral or regional-scale land-use change. Input from stakeholder consultations included recommendations to both address issues around information uncertainty and risk (as explored through the hurdle rates) and to explore the implications of recognising the adoption of new land uses as a social process that occurs over time. This report thus provides side-by-side comparisons of the impact of the uptake curve without a hurdle rate applied (referred to throughout the report as the *Australian National Outlook (ANO) scenario*) with a scenario anchored in the wider literature that applies a hurdle rate (2x) without an uptake curve. This scenario is referred to as the *Central scenario* (and is also reported in Bryan et al. (2014) and Bryan et al. (in review)).

The report also compares the National Outlook findings on Australian land-use change and carbon sequestration potential with other well-known assessments. These studies are significant in the Australian policy context, although not published in journal publications. The report analyses and presents the key reasons for the differences in our findings relative to these previous studies.

1 Introduction

There is significant policy and industry interest in land sector carbon sequestration. The Carbon Farming Initiative and subsequent Emissions Reductions Fund[1] has enabled farmers and land managers since 2012 to participate in a voluntary carbon offsets scheme established by the Australian Government. This has allowed land managers to earn carbon credits by reducing greenhouse gas emissions and storing carbon in vegetation and soils through changes to agricultural and land management practices (DCCEE, 2011). However, the potential amount of abatement, and the implications for land and water use, agricultural production, biodiversity and other ecosystem services are all subject to significant uncertainties over long time horizons (Eady et al., 2009).

The Garnaut Climate Change Review on Australia's response to the challenge of climate change identified substantial potential for sequestration in rural lands (Garnaut, 2008, Lawson et al., 2008). CSIRO (Eady et al., 2009) also examined the potential for land-based greenhouse gas sequestration in more detail and found differences in potential sequestration to those reported in Garnaut (2008). The CSIRO report also identified risks and uncertainties associated with these estimates. For example, Polglase (2009) noted large uncertainties in the estimates of potential areas of reforestation and estimated amounts of CO_2 sequestered for non-harvest plantation forestry. More recent estimates of the abatement potential from reforestation under the Carbon Farming Initiative by ABARES (Burns et al., 2011) for the Australian Treasury are more conservative than earlier ABARE estimates (Lawson et al., 2008).

Recent developments in modelling and analysis have provided an opportunity to refine sequestration estimates. CSIRO has addressed this as part of the *Australian National Outlook 2015* (ANO) report (Hatfield-Dodds et al., 2015) an integrated assessment of a range of possible outlooks for Australian natural resource use and economic and environmental performance. The ANO land-use component includes scenarios involving shifts of agricultural land to carbon plantings (non-harvest, single-species, Eucalyptus plantations) and environmental plantings (bio-diverse mix of native species plantings designed to help recreate local ecosystem composition, structure and function) in emerging land sector markets.

The inclusion of environmental plantings reflects growing international interest in the last two decades in the development of new voluntary mechanisms to reward and encourage landholders for supplying different mixes of food, fibre, and ecosystem services. In Australia, state and federal governments, businesses and non-profit groups have invested money and effort in the design, testing, and implementation of a wide variety of incentives and market-based schemes to provide ecosystem services and encourage environmental improvements, including nature conservation, pollution reduction, carbon sequestration, and improved water quality (Whitten and Coggan, 2013).

[1] http://www.environment.gov.au/climate-change/emissions-reduction-fund/carbon-farming-initiative-project-transition

Land use is central to – and interacts with – food and energy production, water use, ecosystem performance, and economic activity as a whole. The integrated analysis reported here explores the potential implications of interacting uncertainties and provides scenarios for land use change, carbon sequestration, agricultural production, water use, and biodiversity services under a combination of global and domestic scenarios.

This report closely complements two scientific papers of the *Australian National Outlook* – Bryan et al. (2014) and Bryan et al. (in review) – and makes two distinct contributions:

First, the report explores an additional approach to uptake dynamics. We do this by representing inertia in land-use change using an uptake curve which assumes that land use changes over a sixteen year period from when a new land use becomes more profitable than current agricultural use in a specific location, with half of the transition taking place after eight years. This is different from Bryan et al. (2014) and Bryan et al. (in review) which provided sensitivity analysis of uptake and land-use change using 'hurdle rates' that imposed profitability thresholds which must be exceeded before land-use change occurs – an approach well recognised in the literature for providing sensitivity analysis of potential outcomes under uncertain information. However, this approach does not explore other issues that can influence the rate of sectoral or regional-scale land-use change. Input from stakeholder consultations included recommendations to both address issues around information uncertainty and risk (as explored through the hurdle rates) and to explore the implications of recognising the adoption of new land uses as a social process that occurs over time. This report thus provides side-by-side comparisons of the impact of the uptake curve without a hurdle rate applied (referred to throughout the report as the *Australian National Outlook (ANO) scenario*) with a scenario anchored in the wider literature that applies a hurdle rate (2x) without an uptake curve. This scenario is referred to as the *Central scenario* (and is also reported in Bryan et al. (2014) and Bryan et al. (in review)).

Second, the report compares the National Outlook findings on Australian land-use change and carbon sequestration potential with other well-known assessments. These studies are significant in the Australian policy context, although not published in journal publications. The report analyses and presents the key reasons for the differences in our findings relative to these previous studies.

2 Methods

The modelling and analytical framework that was developed for the *ANO* comprises nine linked computer models that represent different components of Australia's economic, electricity and transport sectors, natural resources, and land systems, each located within the global economy. All models provide scenario projections to 2050. A detailed description of the models is provided in (Hatfield-Dodds et al., 2015).

Central to the analysis presented here, the LUTO model is one of these nine models and was used to develop and analyse scenarios of land-use change. The LUTO model is an integrated, environmental-economic model of land use and ecosystem services for Australia, and is described in detail by Connor et al. (2015) and Bryan et al. (2014). LUTO calculates the relative economic returns of different land use options for annual time steps at a spatial resolution of 1.1 km grid cells, for the intensive agricultural land use zone of Australia (the entire non-arid area from south-western Western Australia to eastern Queensland, totalling 85 million hectares) (Figure 1). The model draws on a range of spatial data layers and models of current land use, management practices and inputs, biophysical characteristics and productivity, and costs of production, and combines these with future price, productivity, cost, and demand projections to assess potential output and returns to agriculture and a range of new land use options for each grid cell and year.

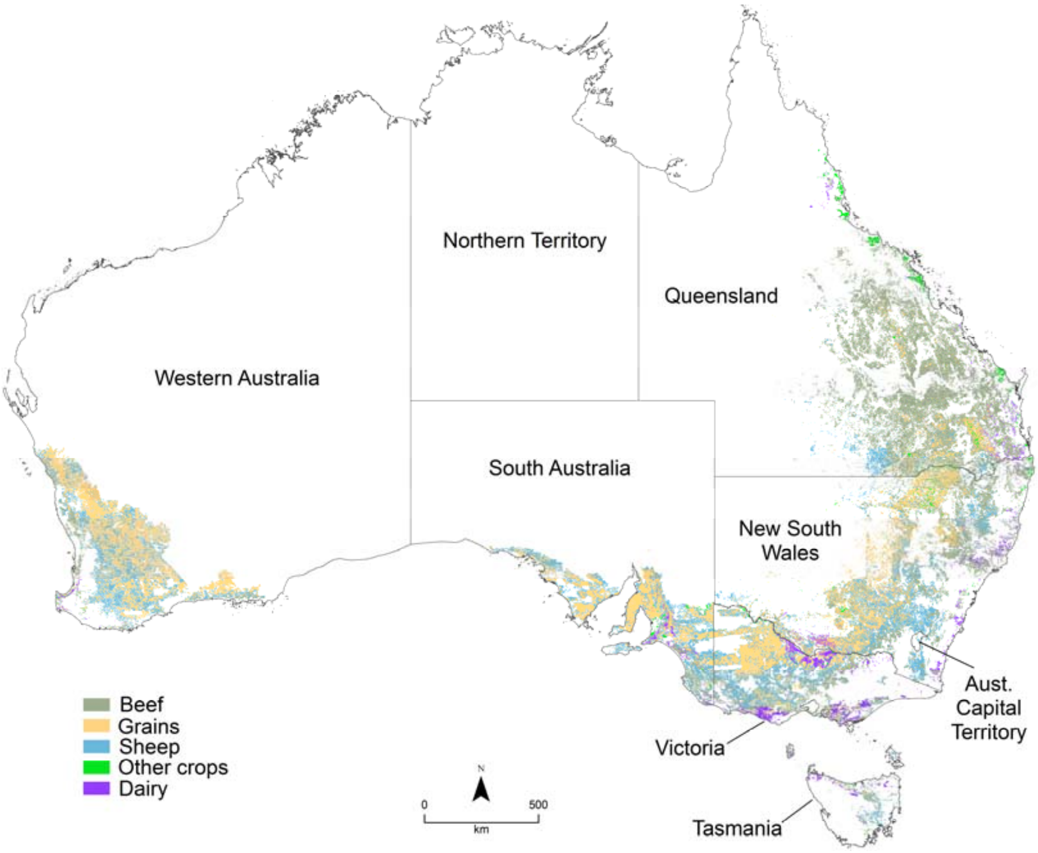


Figure 1. Agricultural land use in the study area, referred to as the intensive agricultural land-use zone

2.1 Global context scenarios

In this study, the supply of carbon sequestration motivated by a carbon market was assessed under four global context scenarios in the period 2013–2050, which represent a range of potential futures. Global trends were considered because Australian economic activity is strongly influenced by global economic trends and conditions. Global demand for food and fibre is shaped by different global outlooks for population, income, and land use. Global emissions and the pace of climate change are shaped by different levels of global abatement effort.

The four global scenarios coded L1, M3, M2 and H3 have different outlooks for global action on climate change and per capita emissions, climate, population, and the size of the global economy, with the world on track to likely temperature increases of 2°C–6°C by 2100 (Table 1). L, M and H refer to the climate outlook and the codes 1, 2 and 3 refer to the population outlook.

Table 1. Summary of the key assumptions for four global scenarios in 2050 and projected temperatures in 2100

	2010	Global Scenarios 2050			
Climate Outlook	uncertain	L	M	M	H
Cumulative emissions (a) Gt CO_2	1089	3,134	3,769	3,769	4588
Temperature increase in 2100 (b)	Uncertain	2°C	3°C –4°C	3°C –4°C	6°C
Population Outlook	Uncertain	1	3	2	3
Population (c) Billion people	6.9	8.1	10.6	9.3	10.6
Abatement Effort	Varied	Very strong	Strong	Moderate	No action
Emissions per person Tpc CO_2e	7.0	3.1	4.4	5.0	8.7
Agricultural Outlook for 2050					
Price increase, grains (d) AUD$	N/A	51%	88%	-4%	39%

Notes: (a) Matches cumulative emissions from 1861–2050 for representative concentration pathways (RCP) 2.6, 4.5 and 8.5 (Moss et al., 2010); (b) Temperature increase shown is for 2090–2099 relative to pre-industrial, upper bound of the 66% range, from Rogelj et al. (2012); (c) Based on UN (2012); (d) The M2 outlook assumes higher global agricultural productivity increase to provide a wider range of export price outlooks for the national analysis. Price increase shown is from 2010–2050 in Australian dollars.

L1 has the lowest emissions and population, with around a 67% chance of limiting the increase in average global temperatures to 2°C or less above preindustrial levels Rogelj et al. (2012). Scenarios M2 and M3 represent mid-range temperature increases, whereas H3 involves no action to reduce global emissions, implying a temperature increase of up to 6°C. The L1, M2 and M3 scenarios involve different degrees of global action to reduce greenhouse gas emissions. Emissions trajectories that limit temperature increases to below 2°C require substantial shifts from current global trends, and so L1 is referred to as involving very strong global action on climate change (i.e. policy to reduce greenhouse gas emissions). The differences in population in the M2 and M3 scenarios give rise to different levels of abatement in order to achieve the same target cumulative emissions by 2050. For this reason M3 is referred to as involving strong action to reduce global emissions and M2 is referred to as involving moderate action to reduce global emissions. Further detail on the global context scenarios is reported in Hatfield-Dodds et al. (2015).

To analyse the potential supply of carbon credits from carbon and environmental plantings under four global scenarios, the LUTO model was linked to other national and global scale environmental and economic models in the suite of ANO models (as summarised in Hatfield-Dodds et al., 2015).

The Global Integrated Assessment Model (GIAM) was used to produce internally consistent emissions pathways and population scenarios, and provide future projections of global climate, oil prices, payments per unit of carbon supplied, and agri-food demand (livestock and grain prices) as inputs to the to the LUTO model (Figure 2). We calibrated global abatement incentives to the cumulative emissions to 2050 for the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCP) 2.6, 4.5 and 8.5 (van Vuuren et al., 2011), corresponding to temperature increases of 2°C, 3°C –4°C and up to 6°C by 2100 (Rogelj et al., 2012). The global emissions trajectories gave rise to four carbon price trajectories (AUD$ per tonne of CO_2e sequestered) with consistent trajectories for oil prices and agricultural commodity export prices. Oil price change correlated with change in the growth of Gross Domestic Product (GDP) (Cai et al., 2015). Scenario-specific exchange rates are provided in Hatfield-Dodds et al. (2015).

Export prices for agricultural commodities were impacted by several factors including population, abatement level, and global agricultural productivity. The modelling assumes that livestock emissions are subject to global abatement incentives and obligations in the very strong abatement scenario (L1) but not in the moderate (M2) and strong (M3) scenarios. M3, with its high population and strong competition for land, had higher crop prices than L1, with its low population and very strong competition for land. For livestock, L1 was higher reflecting the additional global abatement incentives and efforts to reduce livestock emissions. To provide a wider spread of agricultural price outlooks, the M2 scenario assumes higher global agricultural productivity, and so has the lowest agricultural prices.

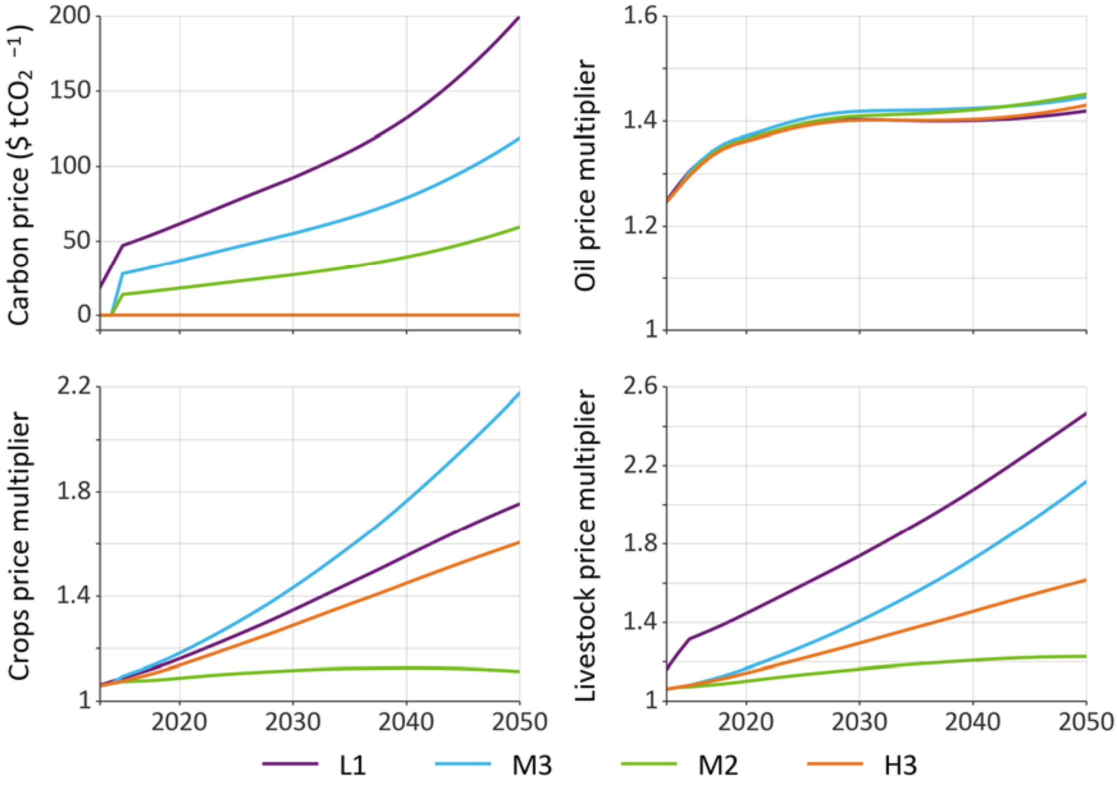


Figure 2. GIAM-modelled trajectories for the global carbon price, agricultural export price multipliers for crops and livestock for Australian producers, and oil price multiplier, under the four global scenarios

2.2 Modelling potential land use change

LUTO quantifies the potential outcomes of competition between existing agriculture and a range of new land uses including bioenergy (biomass-based electricity production), biofuels (transport fuel production), carbon plantings and environmental plantings (Table 2). Energy crops are often in combination with food production. The price trajectories change the relative profitability of agriculture and new land uses over space and time in response to the evolving environmental and economic conditions under the global scenarios and the range of other model parameter settings. Potential areas of land use change are identified where the profitability of new land uses exceeds that of existing agriculture.

Table 2. Agricultural commodities and new land uses considered in the LUTO model

AGRICULTURAL COMMODITIES	NEW LAND USES
• Winter cereals	• Carbon plantings (Eucalyptus monocultures)
• Summer cereals	• Environmental plantings (mixed, local native species)
• Rice	• Biofuels (wheat grain and crop residue)
• Winter legumes	• Biofuels (crop residue only, grain for food)
• Summer legumes	• Biofuels (short rotation Eucalyptus)
• Winter oilseeds	• Bioenergy (crop residue only, grain for food)
• Summer oilseeds	• Bioenergy (short rotation Eucalyptus)
• Sugarcane	
• Pastures and crops for hay	
• Cotton	
• Other non-cereal crops	
• Vegetables	
• Apples	
• Pears and other pome fruit	
• Stone fruit excluding tropical	
• Tropical stone fruit	
• Nuts	
• Plantation fruit	
• Grapes	
• Dairy	
• Beef	
• Sheep	
• Citrus	

Note: Biofuels refers to liquid transport fuel and bioenergy refers to biomass for electricity production.

A range of biophysical and economic parameters were calculated for both agriculture and the new land uses in the LUTO model. Modelling provided estimates of various biophysical parameters of land use over space and time including biomass accumulation and carbon sequestration of reforestation, agricultural yield, water interceptions by trees, bioenergy production, and biodiversity services, as well as the impact of climate change scenarios provided by the global modelling.

The spatial distribution of agricultural yields in the intensive-use zone were mapped using agricultural census data. Yields were adjusted over time for the impact of climate change as outlined in Bryan et al. (2014). Estimates of carbon sequestration rates of fast-growing Eucalyptus plantation species for carbon plantings and a mix of local native vegetation species for environmental plantings were based on the best available estimates (Polglase et al., 2008), and discounted by 20% to provide a general risk buffer and reduce the chance of overstating potential supply of carbon credits (consistent with the approach applied to projects under the Carbon Farming Initiative (Australian Government, 2015)). In addition, financial returns to carbon and environmental plantings account for both fire and drought risk in estimating 'bankable' annual incremental sequestration over time.

A spatially explicit water resource layer was used to estimate the impacts on surface yields from carbon and environmental plantings. We used the Australian Water Resources Assessment system – Landscape model (AWRA-L) (van Dijk, 2010; van Dijk and Renzullo, 2011) to calculate marginal changes in freshwater supply given uptake of tree-based carbon sequestration. Tree-based carbon sequestration impacts on water yield through increased interception and evapotranspiration (Zhang et al., 2001). We used the AWRA-L output of difference in annual water use (ML/ha) between shallow- and deep-rooted vegetation as an estimate of reduced water supply following tree-based carbon sequestration. We report interceptions in catchments with >600 mm average annual rainfall, on the basis that interceptions by trees in these catchments would impact on the amount of surface water runoff reaching streams, and it was taken that there would be little difference between evapotranspiration (and therefore runoff) from areas with vs without trees for low rainfall areas below 600 mm. The 600 mm threshold was based on relationships between long-term average evapotranspiration and rainfall reported in Zhang et al (2001) and we also note that the Australian Government's Carbon Farming Initiative states that permanent tree plantings have the potential to impact on water availability by intercepting surface or groundwater, especially in moderate to high rainfall areas. As a result, tree planting projects are generally excluded from the CFI in areas that receive greater than 600 mm average annual rainfall (with specific exemptions for environmental plantings and the mitigation of dryland salinity) (Australian Government, 2015). Catchments with average annual rainfall >600 mm account for 37% of the study area, or 31.3 Mha.

The modelling assumes new plantations need to buy a water entitlement based on projections of entitlement costs under existing conditions, but does not fully account for price feedbacks that would be expected to occur as a result of water interceptions from new plantations, in part due to the complexity associated with estimating the impact of interceptions on inflows to steams and storages. We have previously found that the area of carbon plantings and environmental plantings, and the supply of carbon credits is not sensitive to differences in the price of water entitlements (Hatfield-Dodds et al., 2015).

In combination with the biophysical modelling, GIAM outputs including the global carbon price and commodity export price index for crops and livestock, and energy price index, were then used to parameterize the economic modelling in LUTO in each year. The spatial distribution of net economic returns to all land uses was quantified each year using a profit at full equity calculation, as described in Bryan et al. (2011), given new markets for carbon and biodiversity, with market-based payments per unit of carbon supplied, and a top-up payment based on biodiversity co-benefits achieved through environmental plantings. The partial equilibrium approach used by LUTO means that as land use change displaces agricultural production through time, the decrease in the supply of agricultural commodities increases the price, and hence, profitability of remaining agricultural production. Supply curves for carbon sequestration and biodiversity over time were estimated, given the potential for land use change from current agriculture to carbon plantings and environmental plantings with the evolving conditions under each global change scenario. The factors accounted for in assessing financial returns to new land uses are outlined in Table 3. Some of these values vary across space in the landscape, reflecting that physical sequestration potential, fire and drought risk, and the costs of establishment (e.g. land preparation and planting) (Summers et al., 2015) vary according to where the planting occurs. For spatial variables, the minimum, median and maximum values are reported, and skewed distributions are evident (e.g. risks to sequestration due to drought and fire). Other variables (e.g. annual management costs) were assumed to be spatially homogenous (i.e. constant regardless of where the plantings occur).

Fire and drought risk were both derived using a statistical technique called survival analysis. Fire frequency for the whole of Australia was calculated based on annual burned areas dataset acquired from Landgate – an agency of the Government of Western Australia – and fire intensity was calculated using Relative Normalised Difference Burn Ratio to quantify the proportion of biomass burned. Drought frequency was calculated based on the drought index calculations of Mpelasoka et al. (2008).

Financial returns to agriculture, bioenergy land uses, carbon plantings, and environmental plantings were calculated each year in net present value terms for each global change scenario over a rolling 100-year horizon, consistent with a 100-year permanence requirement for terrestrial carbon sinks under the Carbon Farming Initiative (Australian Government, 2015). For reforestation land uses, we assumed that landholders make decisions as if they will receive an annuity payment over 100 years based on the present value of carbon sequestration following the typical growth rate of trees over that period. A constant discount rate r = 10% above inflation was used to reflect the commercial returns expected from a high-risk investment. Further detail on the economic assumptions, including those for other land uses, are detailed in Connor et al. (2015) and Bryan et al. (2014).

Table 3. Factors accounted for in assessing financial returns to land sector carbon sequestration, including the minimum, median and maximum values of spatial variables

VARIABLES		SPATIAL		
		Min	Med	Max
Estimated total carbon sequestration (tCO_2 ha^{-1}) *				
Carbon plantings		27	541	1,352
Environmental plantings		5	284	1,291
Fire and drought risk				
% increase in establishment costs due to drought		1.8	2.8	7.4
% decrease in total sequestration due to drought and fire		0.24	0.24	37
Establishment costs (AUD$ ha^{-1}) **				
Carbon plantings		2,304	3,058	4,676
Environmental plantings		1,916	4,361	6,618
Water entitlement for areas with rainfall > than 600 mm (AUD$ ML^{-1}) ***				
Carbon plantings and environmental plantings		246	2,295	4,475
Water use by trees in areas with rainfall > than 600 mm (ML ha^{-1} yr^{-1}) ***				
Carbon plantings and environmental plantings		0.0002	0.656	6.983
Annual management costs (AUD$ ha^{-1})				
Carbon monoculture and environmental plantings	120			
Risk buffer (% decrease in revenue due to uncertainty in carbon sequestration)				
Carbon monoculture and environmental plantings	20			
Discount rate (% per annum)	10			

* Initial values adjusted yearly by productivity and climate impact assumptions
** Initial values adjusted yearly by oil price path
*** Initial values adjusted yearly by climate impact assumptions

2.3 Biodiversity payment policy

The potential for agricultural land to change to environmental plantings and thereby supply biodiversity services was assessed under three illustrative biodiversity policy settings, all involving top-up payments for voluntarily undertaking environmental plantings. The *carbon focused* strategy included market-based payments per unit of carbon supplied, and a top-up payment based on biodiversity co-benefits achieved through environmental plantings, supplemented by a targeted national biodiversity budget (with a budget of AUD$125 million per year, approximating the annual equivalent of the funding under the Biodiversity Fund of the Australian Government's land sector package of the Clean Energy Future plan (Australian Government, 2013), which was spatially allocated each year to maximise biodiversity benefits per dollar of expenditure on environmental plantings. The approach for identifying spatial biodiversity priorities is outlined in Bryan et al. (2014). Biodiversity payments were calculated to match the net present value of the landholders' opportunity cost (the shortfall between environmental plantings and the most profitable land use) and are modelled as a lump sum payment based on net present value. The *balanced focused* settings and *biodiversity focused* settings explore variations on the base settings, by placing a levy on carbon plantings of 15% and 30% of the carbon revenue, respectively, and reallocating this money to the targeted biodiversity payment scheme.

The levy reduces the financial return to landholders for carbon plantings, relative to environmental plantings. It also substantially increases the budget available for targeted 'top up' support for environmental plantings in areas where biodiversity services can be cost-effectively achieved. We quantified the effects of shifting incentives and resources from a carbon focus to a dual focus on both carbon and biodiversity outcomes under these three strategies. This was expressed as a percentage of the maximum biodiversity services possible, the maximum being the total amount of biodiversity services achievable if all grid cells in the study area (which are currently used for agriculture) were converted to environmental plantings.

2.4 Sensitivity analysis

Adoption and uptake dynamics

We also explored potential outcomes under two different approaches to considering the adoption of land use change by landholders. For the first, we specified three hurdle rates (1x, 2x and 5x) for the medium productivity increase scenarios, and one for the reference scenario (1x). For example, for a 2x hurdle rate, new land uses must be more than twice as profitable as the existing agricultural land use to be adopted. A 1x hurdle rate means that land use changes as soon as the new land use exceeds the profitability of the existing use. This provides a sensitivity analysis around the results of the economic calculations, but does not include any explicit representation of sector or regional-scale transition of land use change over time. This approach is well established in the land-use change literature (Bullard et al., 2002; Dumortier, 2013; Murray-Rust et al., 2013; Prestemon and Wear 2000; Schroter et al., 2005), with the 2x hurdle rate more likely to be closer to actual adoption rates rather than 1x. The 5x rate was included as a conservative bound to capture the multiple elements of risk associated with land use change.

The second approach to exploring adoption adjusts the 1x hurdle rate outputs to impose a delay between the year in which carbon plantings outcompete agriculture, and the year in which land use change is deemed to occur. This captures a variety of individual enterprise- and sector- level delays (e.g. the need for individual and collective learning, different appetites for risk and innovation, infrastructure requirements, and institutional adjustments) and was only applied to the uptake of carbon plantings. The uptake delay was not applied to land that switched to environmental plantings either because the income led to this land use outcompeting all other land uses in its own right, or because it received an additional biodiversity payment requiring land-use change to happen at the same time.

Agricultural productivity trends

Two productivity increase scenarios for Australian agriculture were specified within the range of productivity increase trends over the past 35 years (Nossal and Sheng, 2010). Two mid-range productivity increases were investigated: 'medium productivity increase', with annual growth of 1.5% for agriculture and 0.5% for trees; and 'ANO productivity increase', with annual growth of 1.25% for agriculture and 0.467% for trees (simple interest in all cases). The 'reference productivity increase' scenario is based on long run total factor productivity across all sectors from 1977–78 to 2009–10 (Gray et al., 2012) as the best available estimate of 'existing trends' in the context of the ANO scenarios (Hatfield-Dodds et al., 2015). The medium productivity increase level forms a key part of the sensitivity analysis in other ANO reporting.

We do not present a sensitivity analysis across agricultural productivity increase assumptions in this paper, as that is done elsewhere in the ANO reporting (see Grundy et al; in review). Rather, we compare the two mid-range scenarios in the ANO main report where productivity assumptions are applied uniformly across the study area (i.e. they are not spatially variable). They do not explicitly account for climate change impacts.

Land use change to other new land uses did not have an uptake delay imposed because such changes are regarded as more compatible with existing land uses and less likely to be associated with the uptake delays expected for carbon plantings.
The analysis applies the uptake delay using a symmetric, sigmoid-type curve (also known as an 'S' curve), with the effect that 50% of each annual cohort of land changes use eight years from the time the new land use became more profitable than the original use, with 100% changing by 16 years. This was applied to both the medium and reference productivity increase scenarios. The same rates of change applied to the supply of carbon credits from carbon plantings. In parallel, shifts out of agriculture were delayed by an equal and opposite effect. The uptake curve is also well-established as a representation of the dynamics of change in the adoption of agricultural innovations (Rogers, 2003). This approach has the advantage of avoiding very rapid national scale transitions in land use, which appear unlikely to be realised in practice, given that adoption of a new innovation is a process that happens over time. Sixteen years was considered to be a reasonable estimate of social and organizational lags in the early stages of landscape-scale transitions.

Constraints on land use change

The 1x scenarios had an additional capacity constraint applied which restricts the annual area of biofuels and bioenergy plantings, identified as the 'E' constraint. Under this constraint, a maximum of 0.4 GL per annum could be processed, increasing by 50 ML–100 ML per annum to 2020, then increasing by 400 ML per annum. For bioenergy, the maximum that could be processed was 0.2 PJ increasing by 2.5 PJ per annum from 2015. Scenarios that do not have 'E' constraints imposed are identified as 'N' scenarios, where N means 'no constraints'.

Sensitivity combinations

We present a sub-set of the possible scenario combinations described above. We present results for the central scenario (medium productivity, 2x hurdle rate, 15% levy on carbon plantings, no constraints on adoption) and the ANO (ANO productivity increase assumption, a 15% levy on carbon plantings, constraints on bioenergy crop uptake, and imposes the land-use change uptake curve). The effects of different assumptions about the adoption of new land uses can be seen through the comparison of these scenarios. The central scenario and ANO scenario are positioned within this combination of results to provide orientation on how they perform in a larger set of possible outcomes.

Table 4. Summary of scenario components and description of focus scenarios

SCENARIO COMPONENTS	
Global scenarios	L1, M3, M2, H3
Biodiversity policy	0%, 15%, 30% levy on revenue carbon plantings
Productivity increase	Medium, ANO assumption
Hurdle rate	1x, 2x, 5x
Uptake delays	With and without (applied to 1x hurdle rate only)
Capacity constraints	N, E
FOCUS SCENARIOS	**DESCRIPTION**
Central scenario	All global scenarios, all biodiversity policy, medium productivity, 2x hurdle rate, N capacity constraints
ANO scenario	All global scenarios, all biodiversity policy , reference productivity, 1 x hurdle rate, uptake curve, E capacity constraints

3 Results

3.1 Land use change

Under very strong, and strong abatement incentives, the area of potential plantings ranged from approximately 35 Mha to 60 Mha (or approximately 40%–70% of the study area) in 2050 for the L1 global change scenario, and from 22 Mha to 42 Mha (approximately 25%–50% of the study area) for the M3 scenario (Figure 3). The area of plantings under the moderate abatement incentive (M2) was relatively small, ranging from approximately 5 Mha to 15 Mha (5%–18% of the study area). In the M3 scenario there is relatively little land use change to plantings before 2030, and in the M2 scenario there is little change in land use before 2045. Land use change occurs earlier in the L1 scenario.

Medium and reference productivity increase assumptions had minimal effect on the area of plantings. Under strong and very strong abatement incentives for the central scenario in 2050 (identifiable in Figure 3as MP 2x N), total plantings ranged in area from 35 Mha (M3) to 50 Mha (L1). Under the ANO scenario (R 1x E with uptake curve), the area in L1 was higher (approximately 55 Mha).

The uptake curve had the effect of changing the area of plantings such that it tracked the 5x threshold until around 2025 (L1) or 2040 (M3), and then transitioned back towards the 2x adoption hurdle rate, reaching the 2x level between 2030–2040 in L1, and exceeding it thereafter. In M3 the area of plantings with the uptake curve converged to the 2x adoption hurdle rate around 2050. This implies, in general terms, that the uptake curve approach suggests a similar area of plantings as the 2x curve in 2050 in M3, albeit with different transition dynamics.

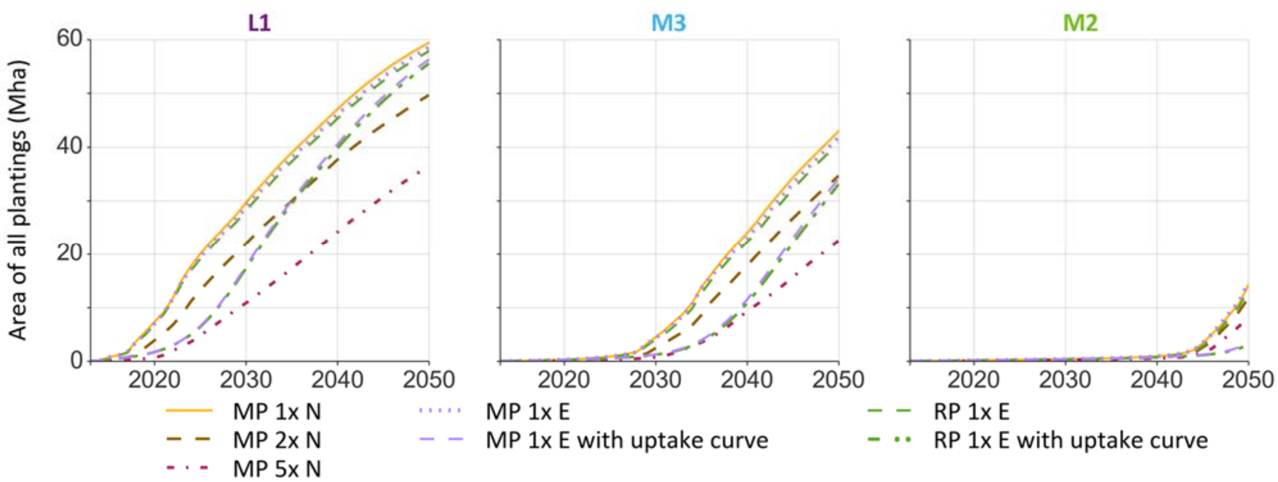


Figure 3. Cumulative area of carbon and environmental plantings from 2013–2050 under two productivity increase settings – ANO productivity increase (RP) and medium productivity increase (MP); 15% levy on carbon plantings biodiversity policy setting; three hurdle rates (1x, 2x, 5x) for the L1, M3 and M2 global scenarios

Notes: The 'central scenario' is represented by the brown 'MP 2x N' dashed line and the 'ANO scenario' is represented by the light green 'RP 1x E with uptake curve' dash-dot-dot line.

We found that carbon and environmental plantings were projected to be the most profitable land use across large areas of Australia's intensive agricultural zone by 2050 under the very strong (L1) and strong (M3) levels of abatement incentives, and across much smaller areas under the moderate abatement incentive (M2). In 2050, plantings become the most profitable land use for up to 58% of Australia's intensive use zone for the medium productivity increase scenario. Removing the 2x hurdle rate of the central scenario takes the area of profitable plantings to up to 70% of Australia's intensive use zone (Figure 4). Also shown in Figure 4, changes in relative profitability become more decisive as trends continue over time, so that by 2050 plantings are more than five times as profitable as existing agricultural use in the majority of areas where plantings are financially attractive.

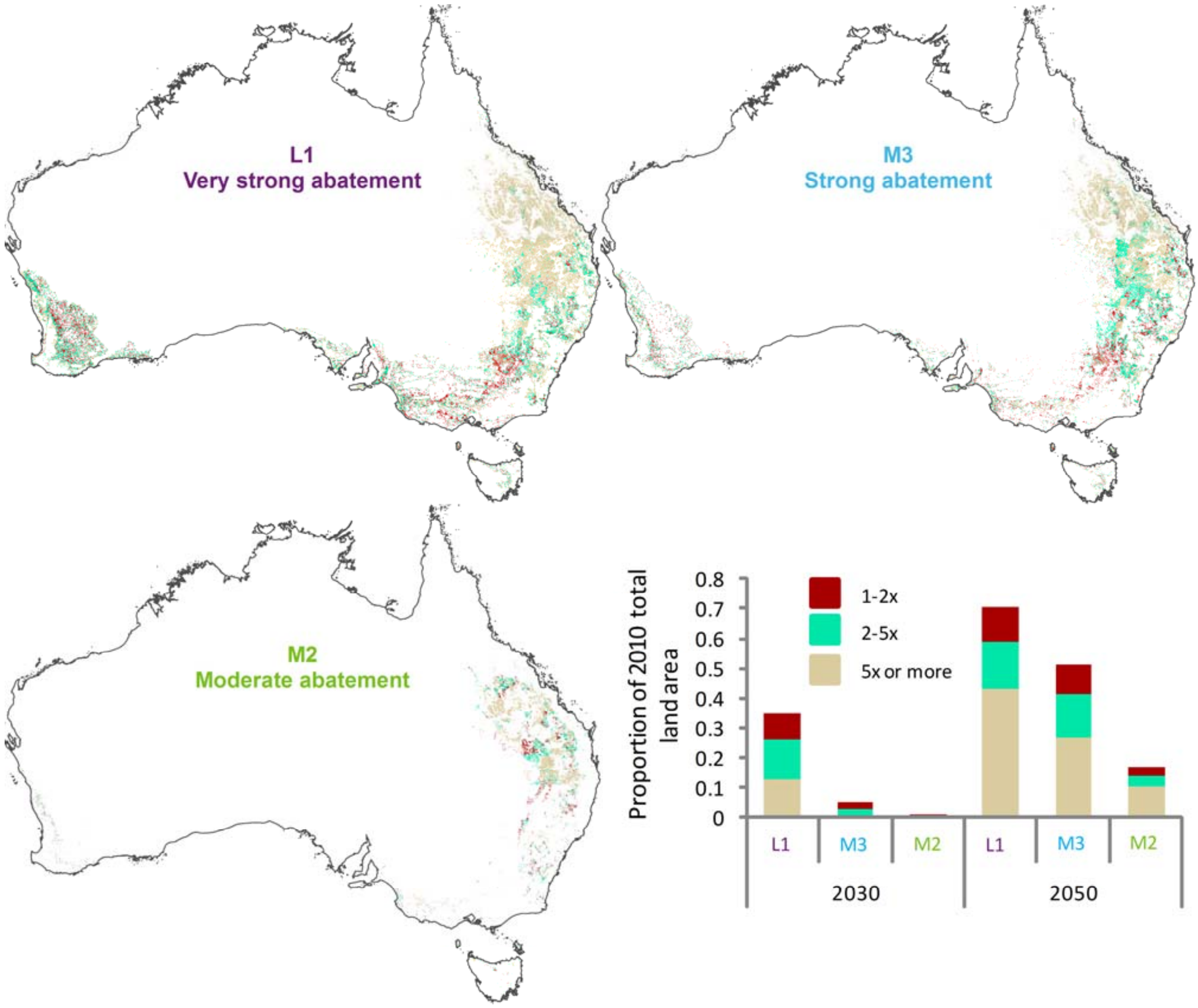


Figure 4. Relative profitability of carbon and environmental plantings as a proportion of total land use area

Notes: Assumes medium productivity increase.

Under very strong and strong abatement efforts for the central scenario, the results indicate that markets for carbon credits have the potential to motivate large areas of land use change into carbon plantings (up to 46 Mha or 54 % of the area at 2050; see L1 strong carbon in Figure 5) but only modest areas into environmental plantings which produce both carbon and biodiversity co-benefits unless policy settings deliberately support these outcomes. Under very strong action for example, environmental plantings increase from 1.4 Mha or 1.6 % in the absence of policy settings to 29 Mha or 34% of the area with implementation of a 30% levy on carbon plantings (Figure 5). In the absence of carbon markets, biodiversity payments result in negligible areas of land use change into environmental plantings. This is illustrated by a comparison of carbon focused settings with biodiversity focused (30% levy on carbon plantings) settings under 'moderate action' and 'no abatement action' global scenarios in Figure 5. Together though, carbon and biodiversity markets have the potential to motivate significant areas of environmental plantings and the supply of biodiversity benefits is highly dependent on combined effects of significant incentives for both carbon sequestration and biodiversity conservation (i.e. L1 strong biodiversity, Figure 5), consistent with Bryan et al. (2014). When significant incentives for carbon and biodiversity combine, large areas of land may be converted to environmental plantings rather than carbon plantings, particularly in the high biodiversity priority areas in the south-west and south-east of Australia (see Figure 6). The extent and patterns of changes in most profitable land uses vary across the landscape. Changes in profitability are most pronounced in areas of livestock grazing in Queensland and New South Wales. These patterns of change are shown in Figure 6.

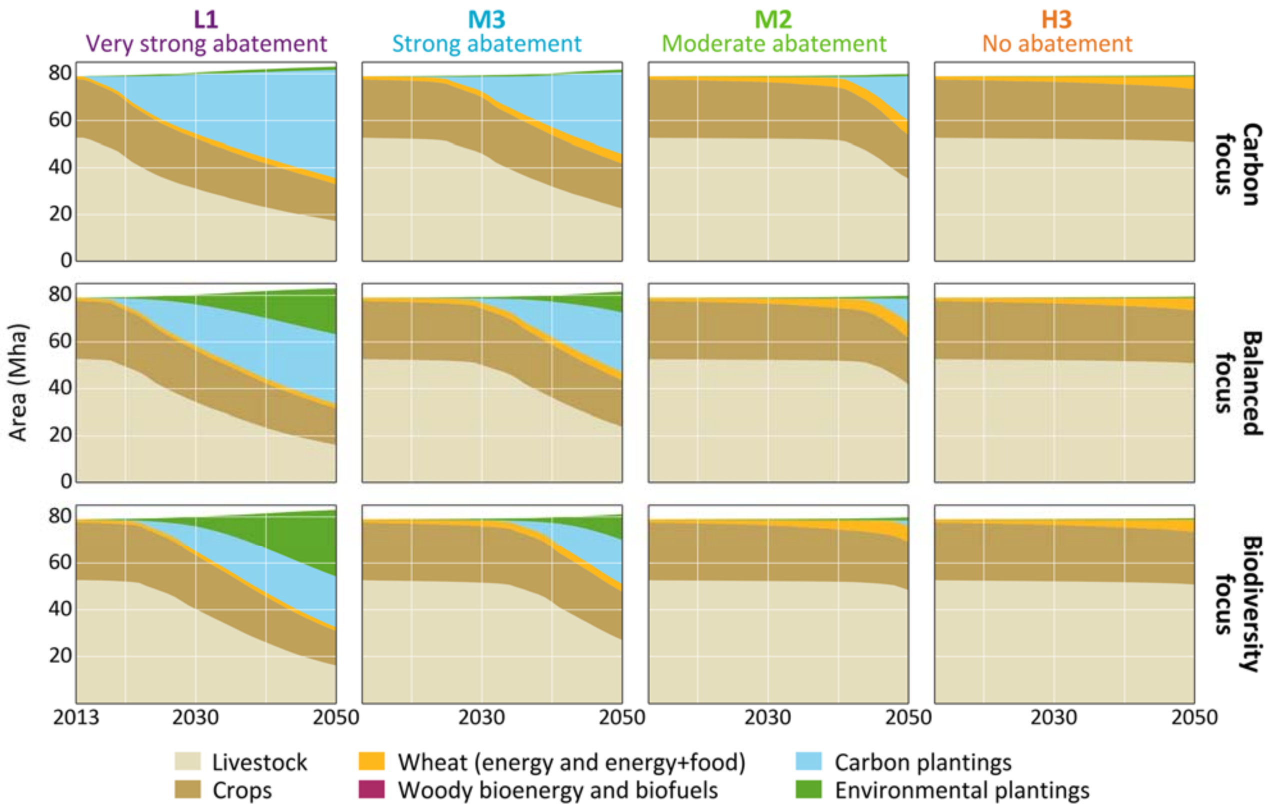


Figure 5. Change in area of potential land use change over time under different global change scenarios and biodiversity policy settings, intensive use zone, 2013–2050, for the central scenario

Notes: This figure shows potential land use over time for medium productivity, 2x hurdle rate. (Appendix Figure A.1 shows the comparable values for the ANO scenario, with and without the uptake delay).

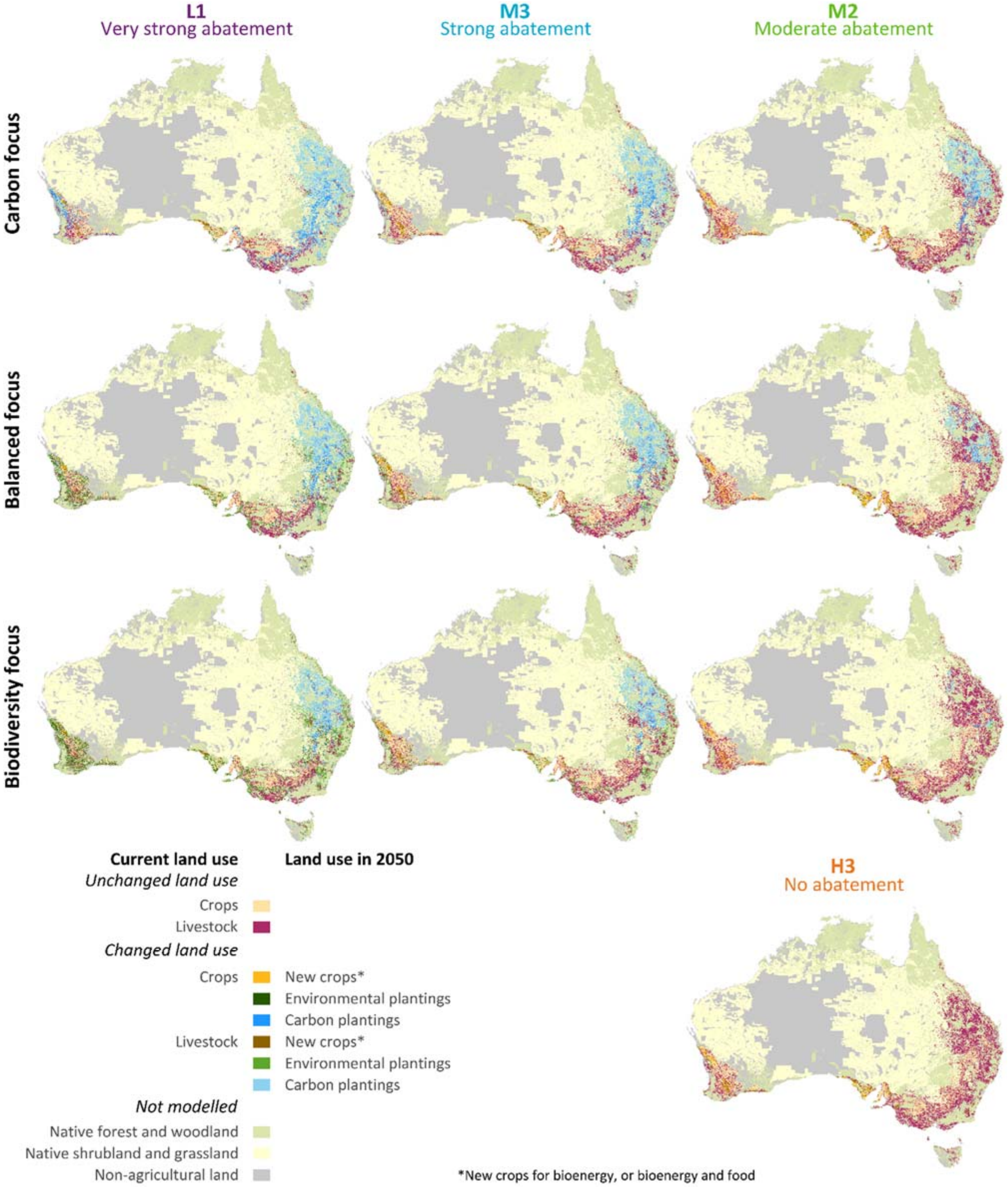


Figure 6. Location of new most profitable land uses across different global change scenarios and biodiversity payment schemes at 2050 (modelled for the intensive use zone) for the central scenario

Notes: Appendix Figure A.2 shows land use change for the ANO scenario.

3.2 Supply of carbon sequestration

Australian landscapes could store substantial amounts of carbon by 2050. The projected supply of carbon credits in 2050 decreased as the abatement incentive decreases and as biodiversity policy settings increasingly favour environmental plantings, reflecting the lower biophysical potential of mixed-species plantings to sequester carbon (Figure 7).

Figure 7 shows supply of carbon offsets has the potential to deliver 0.2 Gt CO_2–13.2 Gt CO_2 (cumulative) for the central scenario and from 0.2 Gt CO_2–11.3 Gt CO_2 for the ANO scenario. In both cases, the GIAM-modelled trajectory of carbon payments combined with the time profile of tree growth and carbon sequestration in biomass resulted in relatively low volumes of carbon being sequestered prior to 2030, even with very high abatement incentives (L1 scenario). The application of the uptake curve reduces the cumulative volume of carbon credits delivered, and delays the peak annual supply of credits. The higher annual flow of carbon permits in 2050 in the ANO scenario is consistent with the larger area of plantings projected for this scenario (see Figure 3 above), reflecting that the central scenario is based on the higher 2x hurdle rate (with no uptake curve), while the ANO scenarios is based on the 1x hurdle rate (with an uptake delay).

With low carbon payments (M2) we found that substantially less carbon would be supplied (0.2 Gt CO_2, cumulative) and this would mostly occur after 2040. This was also the case for the ANO scenario with the uptake curve applied.

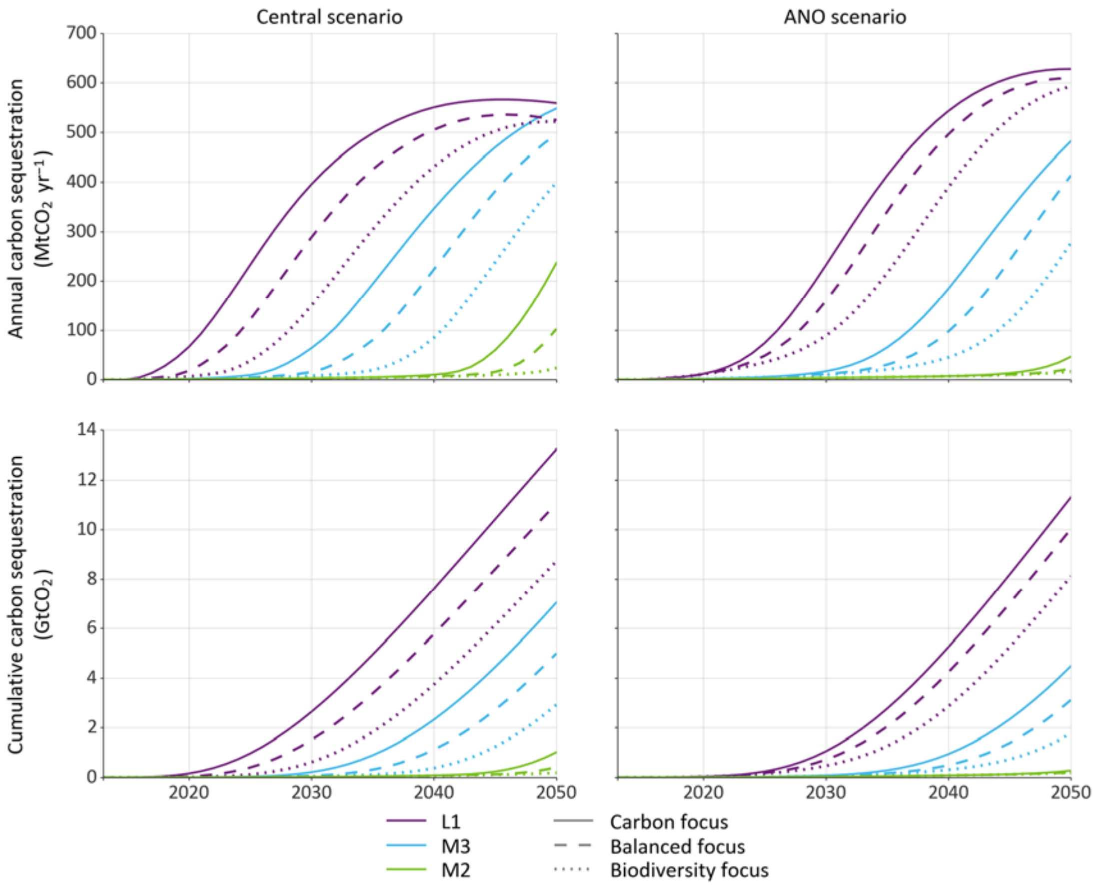


Figure 7. Annual and cumulative supply of land carbon offsets for three global change scenarios at different biodiversity policy settings for the central scenario (left) and the ANO scenario (right)

These patterns of carbon sequestration reflect the more general finding of a clear threshold effect, with very little carbon sequestration being supplied for payments under AUD$50/t$CO_2$, and then substantial volumes being available for payment levels up to around AUD$150/t$CO_2$, after which further increases in payment levels movivate only relatively modest additional supply (see Bryan et al., 2014). The different levels of carbon payments start from different amounts, but follow a similar trajectory over time, so that this AUD$50 threshold is reached almost immediately in the L1 scenarios, around 2025 in the M3 scenarios, and around 2045 in the M2 scenarios (see Figure 2 above).

3.3 Trade-offs and synergies between carbon and biodiversity objectives

For both the central and ANO scenarios, substantial differences in the supply of biodiversity services were found under the global change scenarios, with the greatest supply following the highest abatement incentives and policy settings in favour of environmental plantings.

We define biodiversity services as a form of quality-adjusted area of native vegetation, where zero represents the current area of native vegetation and 100 represents the theoretical maximum biodiversity (with all land returned to native vegetation), not accounting for future climate change. The quality adjustment is calculated on the basis of the biodiversity priority layer used to select the set of plantings that provide the greatest biodiversity benefits for the available funding.

The central and ANO scenarios L1 biodiversity focused settings generated biodiversity services between 69% and 73% of the maximum that could be achieved, respectively. Under all global scenarios presented in Figure 8, strong carbon strategies (that do not provide incentives for biodiversity conservation) are projected to provide up to 10% of the maximum supply of biodiversity that could be achieved.

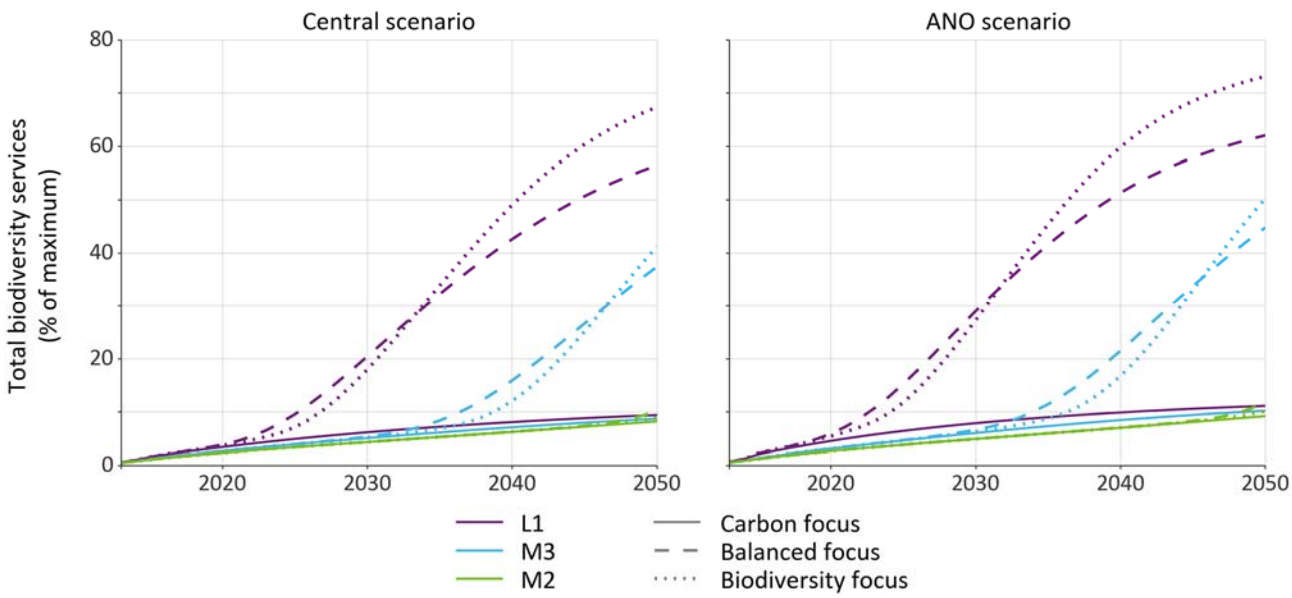


Figure 8. Biodiversity services for the central scenario (left) and the ANO scenario (right)

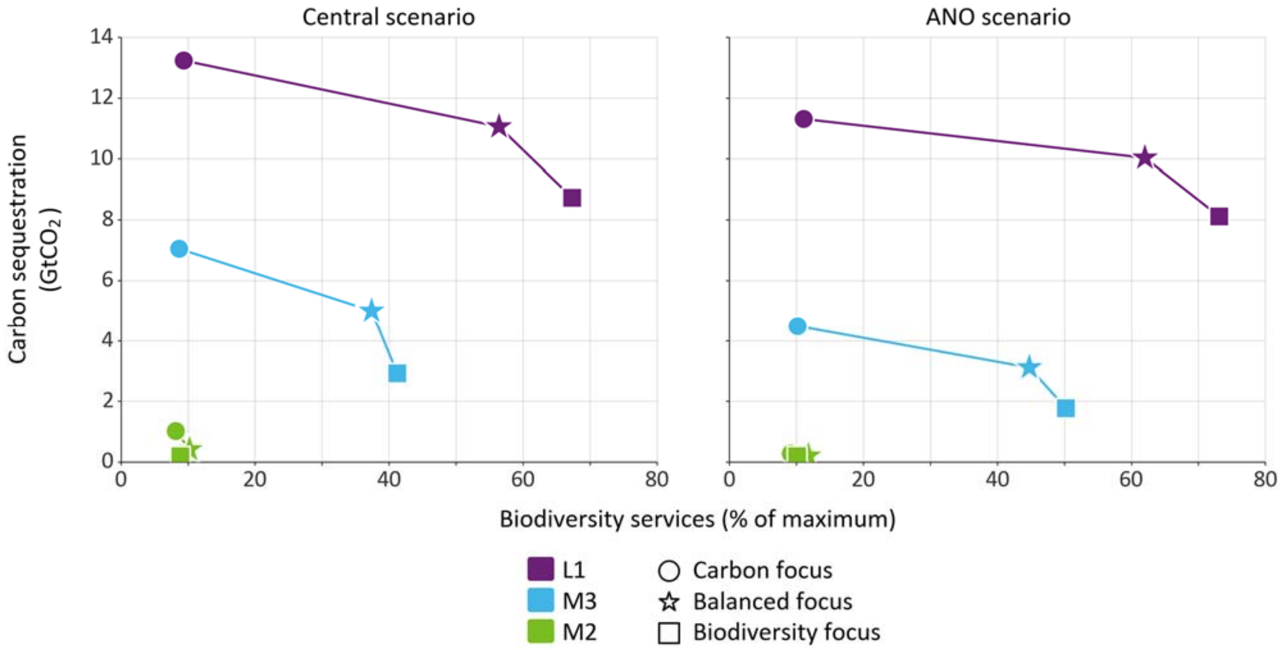


Figure 9 Carbon-biodiversity trade-offs for three global scenarios at different biodiversity policy settings for the central scenario (left) and the ANO scenario (right) at 2050

Figure 9 illustrates the carbon-biodiversity trade-off for the central and ANO scenarios. To explore further using the ANO scenario, the balanced focused settings within the ANO scenario that seeks a mix of carbon sequestration and biodiversity benefits (illustrated by a 15% levy on carbon plantings revenue that is reinvested through the biodiversity fund) could deliver around six times more biodiversity services than a strong carbon strategy (which gives no weight to biodiversity outcomes), but this would entail forgoing around 11% of potential carbon sequestration (L1 scenario). There is a gain of 11–23 Mha of environmental plantings under strong (M3) and very strong (L1) abatement efforts (Figure 10) for a forgone 1.3 Gt CO_2 over the period to 2050 (**Error! Reference source not found.**). Tilting the balance further towards biodiversity (30% levy) is projected to provide much smaller gains in biodiversity services, relative to the loss of carbon sequestration (delivering an additional 3–12 Mha of environmental plantings gains at a sacrifice of 1.4 Gt CO_2–1.9 Gt CO_2) across these scenarios. (See Appendix A.3 and A.4 for changes in the area of carbon plantings under different biodiversity policy settings.)

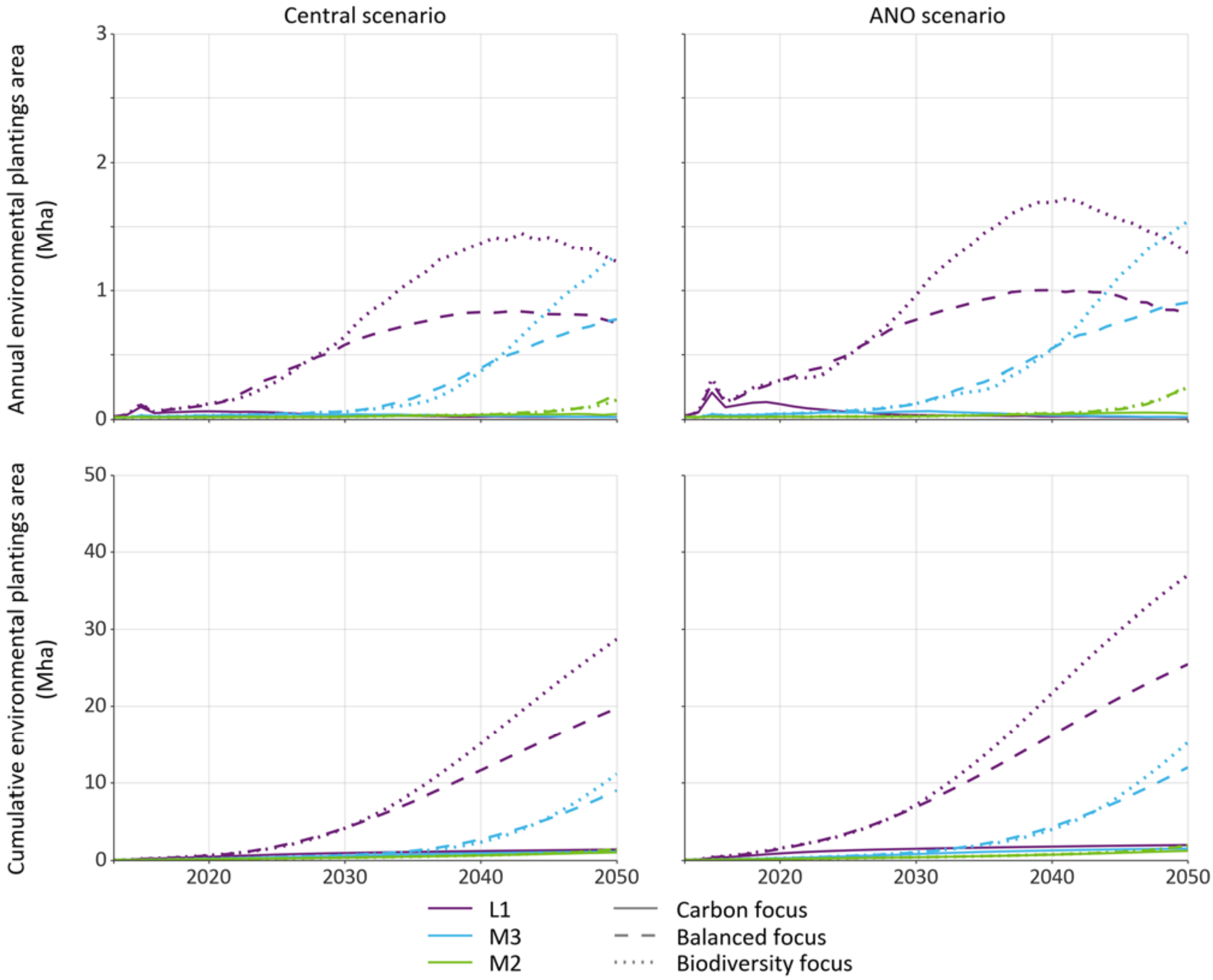


Figure 10 Annual and cumulative environmental plantings area for the central scenario (left) and the ANO scenario (right)

3.4 Agriculture

Productivity improvements resulted in projected volumes of agricultural output increasing over the period 2013–2050 under most scenarios (Figure 11). However, the impact of land use change was larger than productivity improvements in some L1 scenarios (i.e. with very strong abatement incentives), resulting in net declines in total agricultural production. The relative importance of crop and livestock prices is illustrated by the M2 outlook, which assumes little or no price increase over the period. The global scenario (H3) with no abatement action or incentives is also presented.

Grain production across the central and ANO scenarios in 2050 was 48%–73% higher than in 2013 in most outlooks, except under very strong action, where production ranged from -10%–30% from 2013 levels. Very strong abatement incentives motivated early shifts into carbon plantings, resulting in lower grain production than would be the case without land use change.

Outcomes for livestock production were more strongly influenced by potential land use change than crops were. We found incentives for carbon plantings could see a significant change in land use away from livestock within the intensive use zone—up to 31% lower for beef and 44% lower for sheep in 2050 compared with 2013 production (ANO scenarios). Global change scenarios with at least some abatement incentive (i.e. L1, M3, M2) varied significantly from H3, with 2050 beef production ranging from 47%–93% of 2050 H3 production projections, and sheep production ranging from 50%–97% (central scenario). The ANO scenarios projected a similar range, with the lower end of the range further reduced due to the application of the uptake assumptions.

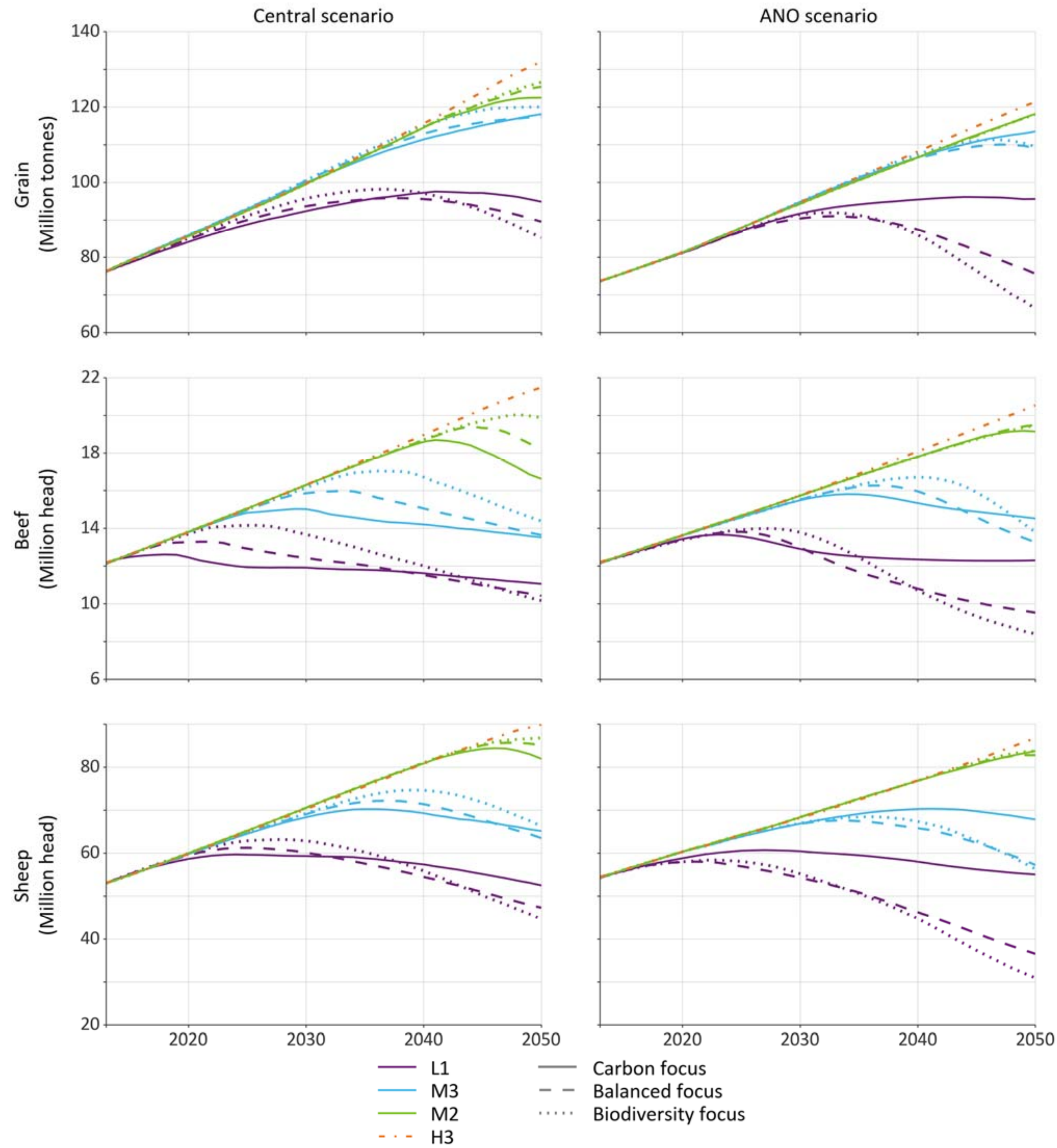


Figure 11. Agricultural output volume 2013–2050 for grain, beef and sheep under different global change scenarios and biodiversity policy settings for the central (left) and ANO scenarios (right)

3.5 Water

We found that uptake of carbon and environmental plantings could have significant impacts on projected surface flows. Water interceptions from new plantings in the central scenario are projected to intercept up to 13.5 TL by 2050 in the M3 (strong abatement) scenarios, and 20 TL in the L1 (very strong abatement) scenarios (Figure 12) in areas where annual rainfall is greater than 600 mm. Interceptions for lower rainfall areas are not reported because of their unlikely effect on surface water flows. Similarly, for the ANO scenario, water interceptions are up to 14 TL by 2050 in the M3 (strong abatement) scenarios and 23 TL in the L1 (very strong abatement) scenarios – these interceptions account for approximately one quarter (M3) to a half (L1) of the total national water use in 2050 in the scenarios with strong or very strong abatement incentives (see Hatfield-Dodds et al. 2015 for details on total water use). These upper limits of the ranges corresponded with the most substantial biodiversity incentives, however, very little difference was observed in 2050 between these incentives and the balanced focused settings. The lower interceptions associated with the biodiversity focused policy setting in the lead up to 2050 reflects the smaller areas of plantings. Interceptions increased over time as the level of carbon payments increases. Water interceptions under the strong carbon settings differed more substantially for the ANO scenario due to the application of the uptake curve to the carbon plantings only.

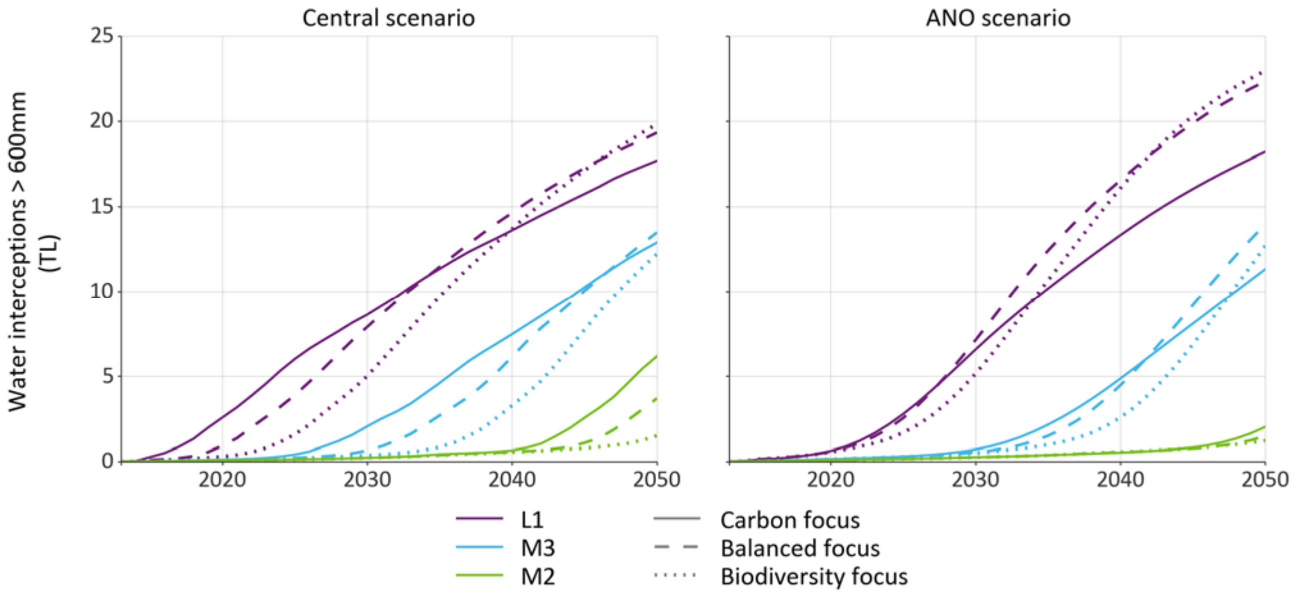
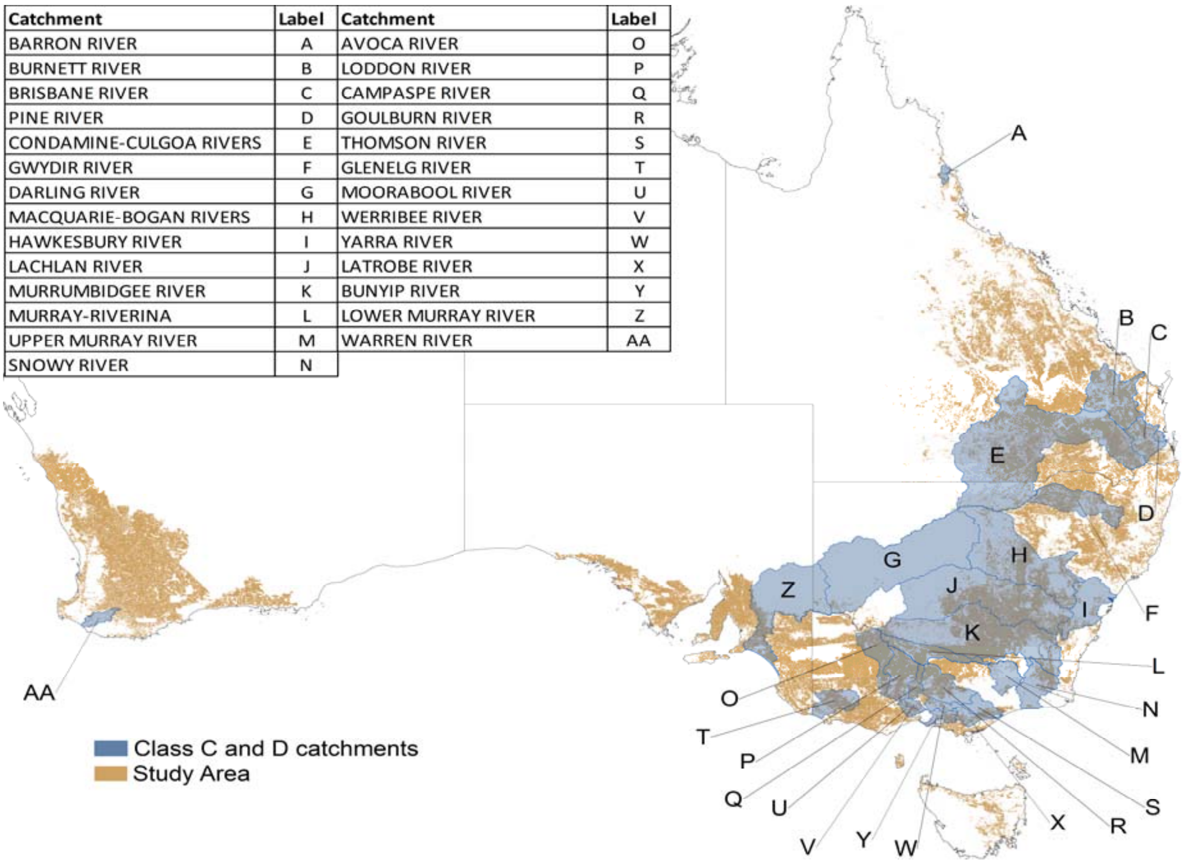


Figure 12. Water interceptions for catchments in areas >600 mm rainfall for the central scenario (left) and the ANO scenario (right)

Water interceptions in the ANO scenario were analysed further, focusing on water extractions from water-limited catchments as a primary indicator of environmental pressure. We found that interceptions from new plantings could have a significant impact on surface flows in water-limited catchments, defined here as Category C and Category D catchments (National Water Commission 2012) and shown in Figure Figure 13. Of the four possible categories of water stress used by the National Water Commission (Categories A–D), Category C are defined as ‘highly water stressed relative to other systems’ and Category D ‘most water stressed’.



Catchment	Label	Catchment	Label
BARRON RIVER	A	AVOCA RIVER	O
BURNETT RIVER	B	LODDON RIVER	P
BRISBANE RIVER	C	CAMPASPE RIVER	Q
PINE RIVER	D	GOULBURN RIVER	R
CONDAMINE-CULGOA RIVERS	E	THOMSON RIVER	S
GWYDIR RIVER	F	GLENELG RIVER	T
DARLING RIVER	G	MOORABOOL RIVER	U
MACQUARIE-BOGAN RIVERS	H	WERRIBEE RIVER	V
HAWKESBURY RIVER	I	YARRA RIVER	W
LACHLAN RIVER	J	LATROBE RIVER	X
MURRUMBIDGEE RIVER	K	BUNYIP RIVER	Y
MURRAY-RIVERINA	L	LOWER MURRAY RIVER	Z
UPPER MURRAY RIVER	M	WARREN RIVER	AA
SNOWY RIVER	N		

Figure 13. Category C and D water-limited catchments

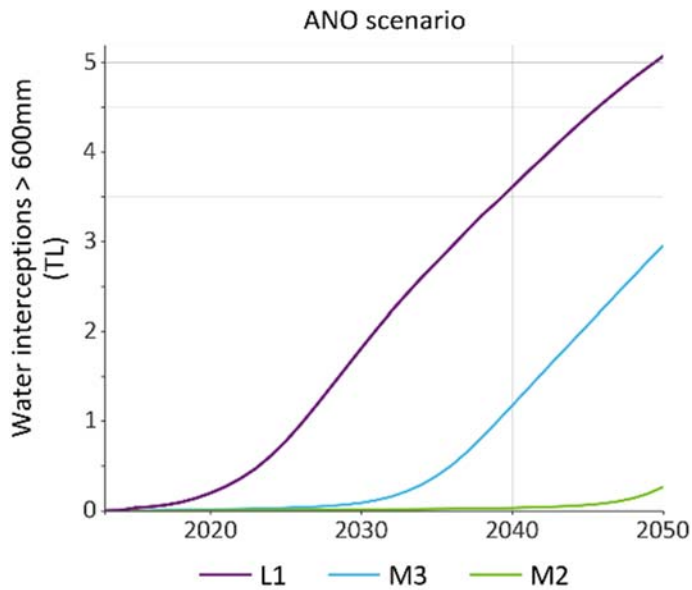


Figure 14. Water interceptions in water-limited catchments for the ANO scenario, balanced focused settings only reported

Under the balanced focused, new plantings intercepted up to 2.95 TL by 2050 in the M3 (strong abatement) scenarios, and 5.06 TL in the L1 (very strong abatement) scenarios across all catchments (Figure 14). Interceptions were very small in comparison for the moderate action (M2) scenario.

As an indication of the trade-offs involved, combined carbon and environmental plantings in Class C and D water-limited catchments under very strong abatement (L1) incentives account for 21% of total water intercepted in areas with greater than 600 mm annual rainfall, approximately 10% of national water use (based on national water use of 45 TL reported in Hatfield-Dodds et al., 2015), and up to 2.2 Gt CO_2 (or 22%) of cumulative national land sector sequestration (Figure 15) over the period to 2050.

Under strong (M3 abatement incentives), carbon plantings in Category C and D catchments likewise account for approximately 20% of total interceptions for the scenario, 6% of national water use, but contribute only 0.8 Gt CO_2 (or 8%) of cumulative national land sector sequestration over the period to 2050.

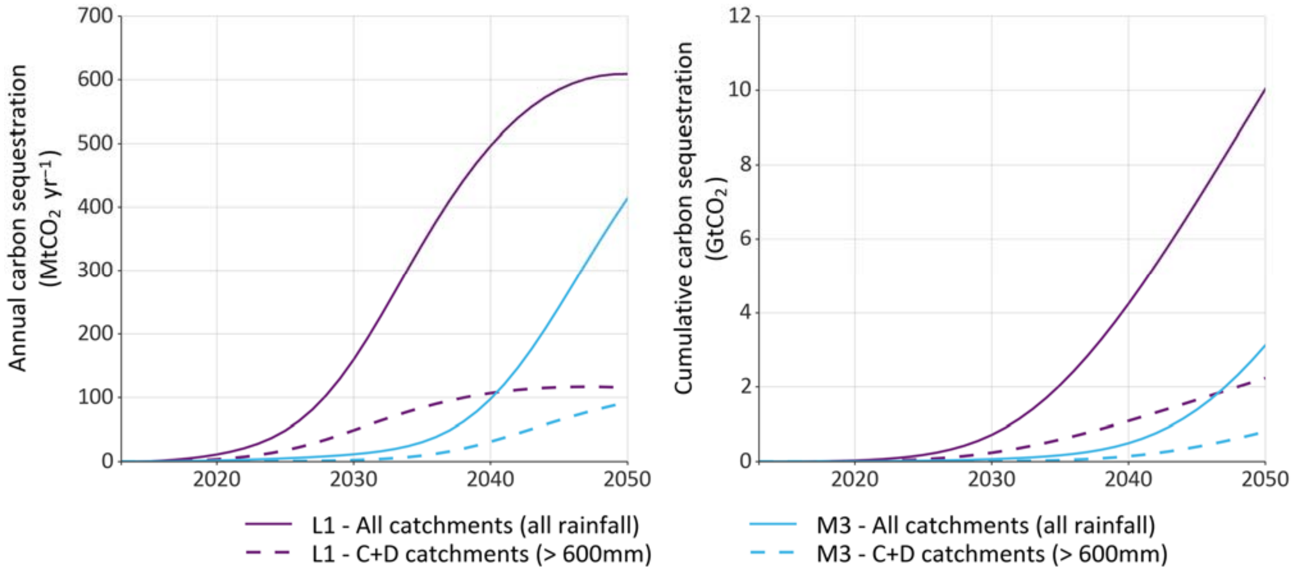


Figure 15. Annual supply of carbon sequestration for the L1 and M3 global scenarios for the ANO scenario. Carbon sequestration in water-limited catchments is also shown.

4 Comparison to previous studies

Our results differ from other previous assessments of land use change and carbon sequestration potential in Australia including Lawson et al. (2008), Burns et al. (2011), Eady et al. (2009), and Polglase et al. (2013). There are large differences in the findings of these studies driven primarily by assumptions around two key variables: the rates of potential land use change as determined by the choice of a range of sensitive economic and behavioural parameters; and the rates of carbon sequestration by trees. Further differences between this study and all previous studies result from our use of changes in key environmental and economic parameters estimated from internally consistent global change scenarios modelled in the integrated assessment.

ANO methods and assumptions imply that land-sector carbon markets have the potential to deliver 12–54 times the amount of abatement estimated by Burns et al. (2011), depending on the strength of the carbon price incentive (Table 5).

Table 5. Comparison of Australian National Outlook (ANO) estimates of sequestration with Burns et al. (2011)

	STRONG CARBON PRICE INCENTIVES (AUD$23–$140/tC0$_2$e over 2015–2050)		VERY STRONG CARBON PRICE INCENTIVES (AUD$47–$285/tC0$_2$e over 2015–2050)	
	Environmental plantings	**All plantings**	**Environmental plantings**	**All plantings**
Burns et al. (2011)	36,695	72,393	600,249	865,138
ANO estimate	231,013	3,897,156	394,746	10,121,801
Ratio (ANO: Burns et al)	6.30	53.80	0.66	11.70

Note: The price range in the table represents starting and ending prices over the period 2015 to 2050.

Most of this difference is accounted for by the more recent (28% higher) estimates of average sequestration per hectare used in the ANO projections, which in turn result in a much larger area of land being profitable for carbon plantings. Together these factors result in ANO sequestration estimates for environmental plantings being 4.65–9.11 times larger than those in Burns et al. (2011). Other factors work in the opposite direction, reducing the total difference. Table 6 presents a decomposition analysis that replicates the assumptions from Burns et al. (2011) for carbon payments and tree growth, and systematically compares these and other factors to the ANO analysis. Due to differences in the framing of the analysis it is only possible to compare our assumptions with those of Burns et al. (2011) for sequestration from environmental plantings.

The ANO analysis draws on more recent estimates of sequestration per hectare (Polglase et al. 2008), that are 1.28 times (or 28% higher) than the Burns et al. (2011) estimate, on average. This gives rise to a spatial selection effect, as market incentives encourage plantings on land areas that are able to sequester greater carbon. Combined with the higher biophysical sequestration under average conditions, this results in ANO sequestration per hectare being 2.01–2.31 higher (Table 6). Higher returns per hectare result in a larger area of land being profitable for carbon credits from environmental plantings, with the area being 2.01–4.52 times larger.

Controlling for the assumed level and time path of payments in the ANO analysis resulted in lower estimated sequestration, through impacting on the year when the payment level reaches the crucial AUD$40–$50 threshold (discussed above, and see Bryan et al. 2014).

Other factors were found to increase or decrease carbon sequestration from environmental plantings. This was likely to reflect two main effects. First, the two studies use different methods to establish opportunity costs, with Burns et al. (2011) using current land values while the ANO modelling estimates future opportunity costs (and land values) based on the economic returns of current and alternative land uses based on physical productivity, unit input costs, and farm gate output prices. Second, the Burns et al. (2011) method assumed that environmental plantings were competitive against non-native plantations, with environmental plantings supplying 51%–69% of total sequestration, whereas the ANO analysis determines that environmental plantings are relatively marginal, supplying 4%–6% of total sequestration (based on analysis in Polglase et al. 2008).

Table 6. Decomposition of underlying drivers of results relative to Burns et al. (2011) for environmental plantings

STRONG CARBON PRICE INCENTIVE (AUD$23–$140/tCO_2e over 2015–2050)	RELATIVE SEQUESTRATION EFFECTS (Environmental plantings)		TOTAL SEQUESTRATION 2013–2050 (tCO_2e)
	Individually	Combined	Environmental plantings
Burns et al 2011		1.00	36,695
Total sequestration			
Sequestration rate	1.28	1.28	46,998
Spatial selection effort	1.57	2.01	73,938
Area effort	4.52	9.11	334,118
Carbon price differences	0.56	5.08	186,436
Other variations	1.24	6.30	231,013
ANO estimate		6.30	231,013

STRONG CARBON PRICE INCENTIVE (AUD$47–$285/tCO_2e over 2015–2050)	RELATIVE SEQUESTRATION EFFECTS (Environmental plantings)		TOTAL SEQUESTRATION 2013–2050 (tCO_2e)
	Individually	Combined	Environmental plantings
Burns et al 2011		1.00	600,249
Total sequestration			
Sequestration rate	1.28	1.28	768,780
Spatial selection effort	1.80	2.31	1,385,355
Area effort	2.01	4.65	2,790,104
Carbon price differences	0.48	2.24	1,342,009
Other variations	0.29	0.66	394,746
ANO estimate		0.66	394,746

5 Discussion

With substantial price incentives, carbon plantings and environmental plantings have significant potential to supply carbon credits from Australia's agricultural land. We find that it would be technically feasible and commercially attractive for carbon plantings to provide up to 11.3–13.2 Gt CO_2 in cumulative sequestration over the period to 2050 (depending on assumptions about land use change) with average annual abatement of up to 513 Mt CO_2 over the period 2031–2050. This analysis assumes carbon payments that are broadly consistent with the carbon price trajectories in the medium and high scenarios modelled by The Treasury (2011) and The Treasury and DIICCSRTE (2013).

In broad terms, this suggests that plantings-based land sector abatement has the potential to supply between one third and one half of Australia's total abatement potential from 2031–2050, assuming substantial abatement of direct emissions from other sectors (such as projected in the strong and very strong scenarios for the National Outlook (Hatfield-Dodds et al., 2015), the medium or high price scenarios in Treasury (2011), or the ClimateWorks Australia et al. (2014) deep decarbonisation pathways analysis).

The analysis explores a number of technical issues in estimating the technical potential for carbon sequestration, and associated synergies and trade-offs for biodiversity and water resources. The physical sequestration rates of carbon plantings and environmental plantings are a key input to the analysis. The modelling uses the best available estimates of carbon sequestration (Polglase et al., 2008) and discounts them by 20% to reduce the risk of overstating potential supply of carbon credits. As described above, increases in sequestration rate multiply through the supply chain: increasing returns to plantings per hectare, which increases the area attractive for plantations, which interacts to further boost supply; this is a key explanation of the differences between the findings presented here and those of Burns et al. (2011).

The modelling results provide valuable insights into physically achievable carbon sequestration assuming trend rainfall, climate, fire and drought risk. It does not account for the potential impacts of increased drought events due to climate change (drought risk is assumed constant over time), or prolonged wet periods, which could result in higher or lower volumes of sequestration in particular years. The analysis does not include potential abatement from enhanced soil carbon or from management of savannah burning. In relation to agricultural land use, the analysis assumes that no new higher-value agricultural land uses or farming systems become available before 2050.

We included a representation of an uptake lag and used hurdle rates to explore uncertainties about relative profitability. The analysis, however, does not attempt to account for potential societal constraints, such as 'social licence' issues around large-scale plantations and land-use change. Neither does it seek to evaluate or comment on the desirability of different potential futures from the perspectives of different stakeholders. We consider these issues would benefit from a robust public discussion about the merits of different potential patterns of land use, and the suite of options available to promote healthy landscapes and communities in a dynamic and evolving world.

Over the very long term, it is important to recognise that reafforestation potential is limited by the pre-existing extent of cleared land. This implies that carbon plantings can be considered to be a form of transition strategy for reducing global carbon emissions. The sequestration from new plantings in any specific location rise to a peak, and then decline due to the physical profile of carbon sequestration as planting mature. This implies a physical limit to the total abatement potential from revegetation, and thus that reforestation provides a temporary wedge, buying time for long-term low-carbon structural changes in the energy sector and broader economy. Over the longer term, it might be possible to develop bioenergy with carbon capture and storage as a means for achieving ongoing net reductions in global concentrations of atmospheric carbon – but specific technology strategies are only speculative at this stage (Fuss et al., 2014).

It is also important to note that the upper end of this technical sequestration potential would involve unprecedented levels of land use change from existing agricultural use. While our analysis finds that these scenarios would provide net benefits to land owners (increasing incomes, and diversifying income sources), the analysis does not account for effects on regional communities, and does not fully explore some aspects of projected biophysical changes, such as soil carbon, erosion, sedimentation, water quality, amenity and recreational values. The projections are also contingent on sustained action and incentives to reduce emissions, which underpin the assumed trajectories for carbon sequestration payments.

We find pronounced threshold effects in the national supply of credits; with relatively low volumes of abatement provided at low levels of carbon payments (see Bryan et al., 2014). The time profile of biophysical carbon sequestration and assumptions about the timing of land use change together result in low volumes of credits being delivered prior to 2030 across all scenarios explored, even those with very high payments. New tree plantations have high upfront investment costs, long project life and long payoff periods given the time taken for trees to reach their peak sequestration rate. In general, investors would require stronger financial incentives to deliver carbon (and other benefits) where they bear more policy-related risks, but are likely to supply sequestration at lower payment levels where these risks are shared or borne by others (such as through long-term contracts). National and international experience with market-based environmental policies indicates that confidence in long-term institutional settings is central to achieving policy objectives that require long-term private investments. Carbon sequestration lag times and adoption lag times imply that investors would need confidence in policy settings (perhaps bolstered by contractual arrangements for future payments for demonstrated sequestration) before investing.

Increasing both agricultural production and carbon sequestration can be achieved simultaneously under the productivity assumptions of the analysis, but maximum food production in 2050 was always highest without any abatement effort (H3 scenario). Under the very strong abatement incentives, production of some agri-food commodities also had the potential to fall below current production levels, particularly for livestock industries. We assumed that global stable or rising agricultural commodity prices, in contrast to observed price declines over the decades before 2000. All else equal, a rising price trend would reduce the volume of land sector abatement, by increasing the returns to agricultural land use. Conversely, falling agricultural prices would result in higher cumulative abatement by 2050 due to the reduced competitiveness of agriculture. Outcomes for food production under higher and lower productivity increase assumptions for the global scenarios examined in this paper have been reported by Grundy et al. (in review).

The emissions reduction opportunity offered by land-sector abatement also creates co-benefit opportunities in the supply of biodiversity services. Importantly, a carbon market alone does not generate substantial biodiversity services from Australia’s agricultural land. Over most of the study area, the sequestration ability, and therefore the profitability of mixed species plantings was far exceeded by the high-growth tree species typically used in carbon plantings. However, when complemented by policy settings that levy carbon plantings and target cost-effective payments for biodiversity services, the area of environmental plantings was increased considerably.

We found that the rates of uptake of carbon plantings and environmental plantings could have significant impacts on projected surface flows, and thus on national water consumption. The analysis is focused on changes to surface water flows from climate change and land use change, and excludes groundwater. Water interceptions by trees account for 25–50% of total national water use in 2050 in the scenarios with strong or very strong abatement incentives (Hatfield-Dodds et al., 2015). As an indication of the trade-offs involved, carbon plantings in Australia's most water-limited catchments account for up to 21% of total interceptions, up to 10% of national water use. Up to 2.2 Gt CO_2 of cumulative national land sector sequestration over the period to 2050 is sequestered in these areas. Changes in water licence prices make little difference to the area of plantings or the volume of sequestration (Hatfield-Dodds et al., 2015). These findings illustrate both the significance of potential changes in surface flows from land use change, and the potential scale of the impacts and unintended consequences that could arise from governance arrangements that do not account for and manage cross-sector interactions. We note here that the analysis excludes groundwater but we acknowledge that stress on groundwater systems may increase from carbon and environmental plantings.

These findings illustrate the need to understand the interactions between policy settings – some will involve synergies, others trade-offs. This has also been demonstrated by Bryan and Crossman (2013) and Bryan et al. (2015).

6 Conclusion

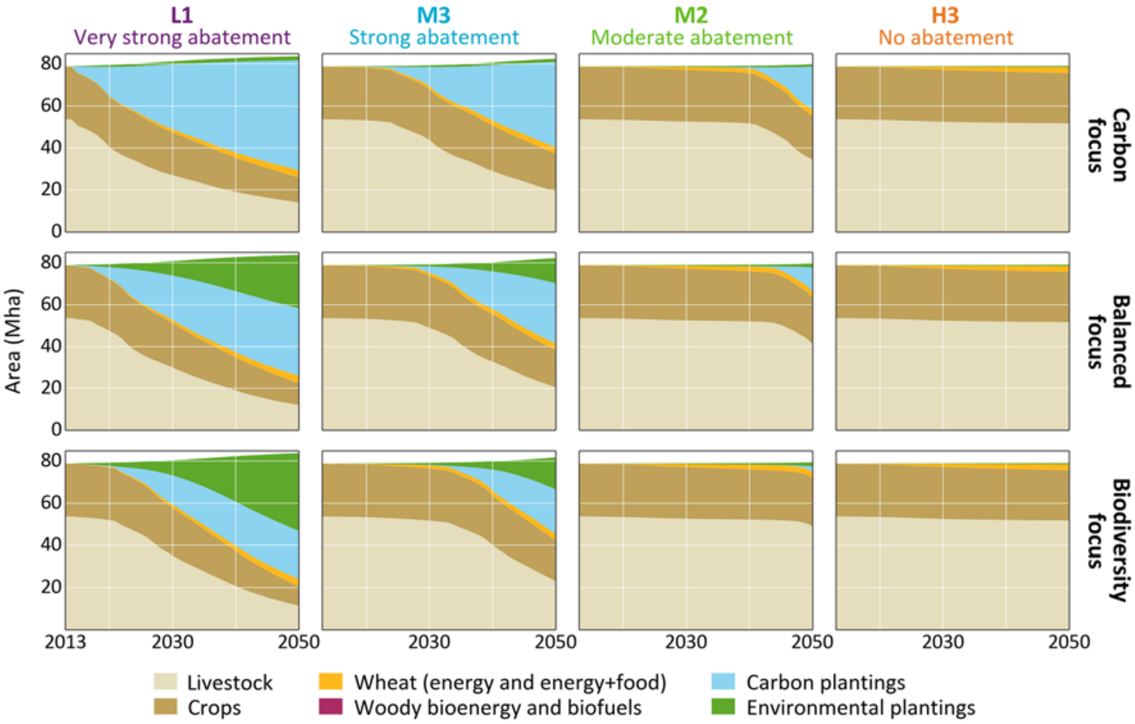
With commercially attractive price incentives, carbon plantings and environmental plantings have significant potential to supply carbon credits from Australia's agricultural land. We find that carbon plantings have the technical potential to provide up to 11.3 to 13.2 Gt CO_2 in cumulative sequestration over the period to 2050, assuming payments per unit of carbon supplied that are broadly consistent with the carbon price trajectories in the medium and high scenarios modelled by The Treasury (2011) and The Treasury and the DIICCSRTE (2013). In broad terms, this suggests that plantings-based land sector abatement has the potential to supply between one third and one half of Australia's total abatement potential from 2031–2050, substantial abatement of direct emissions from other sectors. The projections are also contingent on sustained global action to reduce emissions, which underpin the assumed trajectories for carbon sequestration payments.

The time profile of biophysical carbon sequestration and assumptions about the timing of land use change together result in low volumes of credits being delivered prior to 2030 across all scenarios explored, even those with very high carbon payments. Over the period 2031–2050, we find average annual abatement of up to 513 Mt CO_2. Over the very long term, carbon plantings can be thought of as a form of transition strategy for reducing global carbon emissions, while providing more time to develop and deploy cost effective energy and industrial technologies. The sequestration from new plantings in any specific location rise to a peak, and then decline due to the physical profile of carbon sequestration as plantings mature. This implies a physical limit to the total abatement potential from re-vegetation, and thus that reforestation provides a temporary wedge, buying time for long term low-carbon structural changes in the energy sector and broader economy.

It is also important to note that the upper end of this technical sequestration potential would involve unprecedented levels of land use change from existing agricultural use. While the analysis explores a number of issues in estimating the technical potential for carbon sequestration, and associated synergies and trade-offs for biodiversity and water resources, it does not attempt to account for potential societal constraints around large scale plantations and land use change. We consider these issues would benefit from robust public discussion about the merits of different potential patterns of land use – and how to accommodate associated private and public interests – in a dynamic and evolving world.

Appendix A:

Most profitable land use



Land use accounting for uptake lag

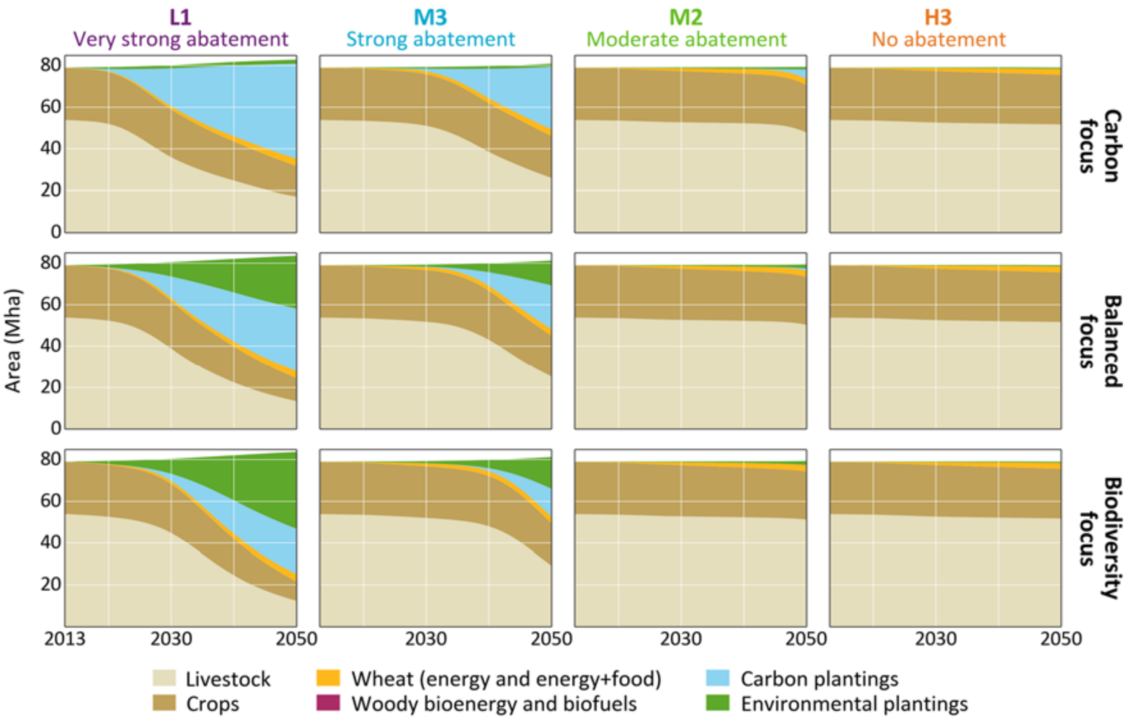


Figure A.1. Change in shares of most profitable land use over time under different global change scenarios and biodiversity policy settings, intensive use zone, 2013–2050, for the ANO scenario

Notes: This figure shows most profitable land use over time for reference productivity increase (1x hurdle rate). Panel (a) shows most profitable land use over time, and Panel (b) shows projected land use accounting for the uptake lag, as discussed in the text.

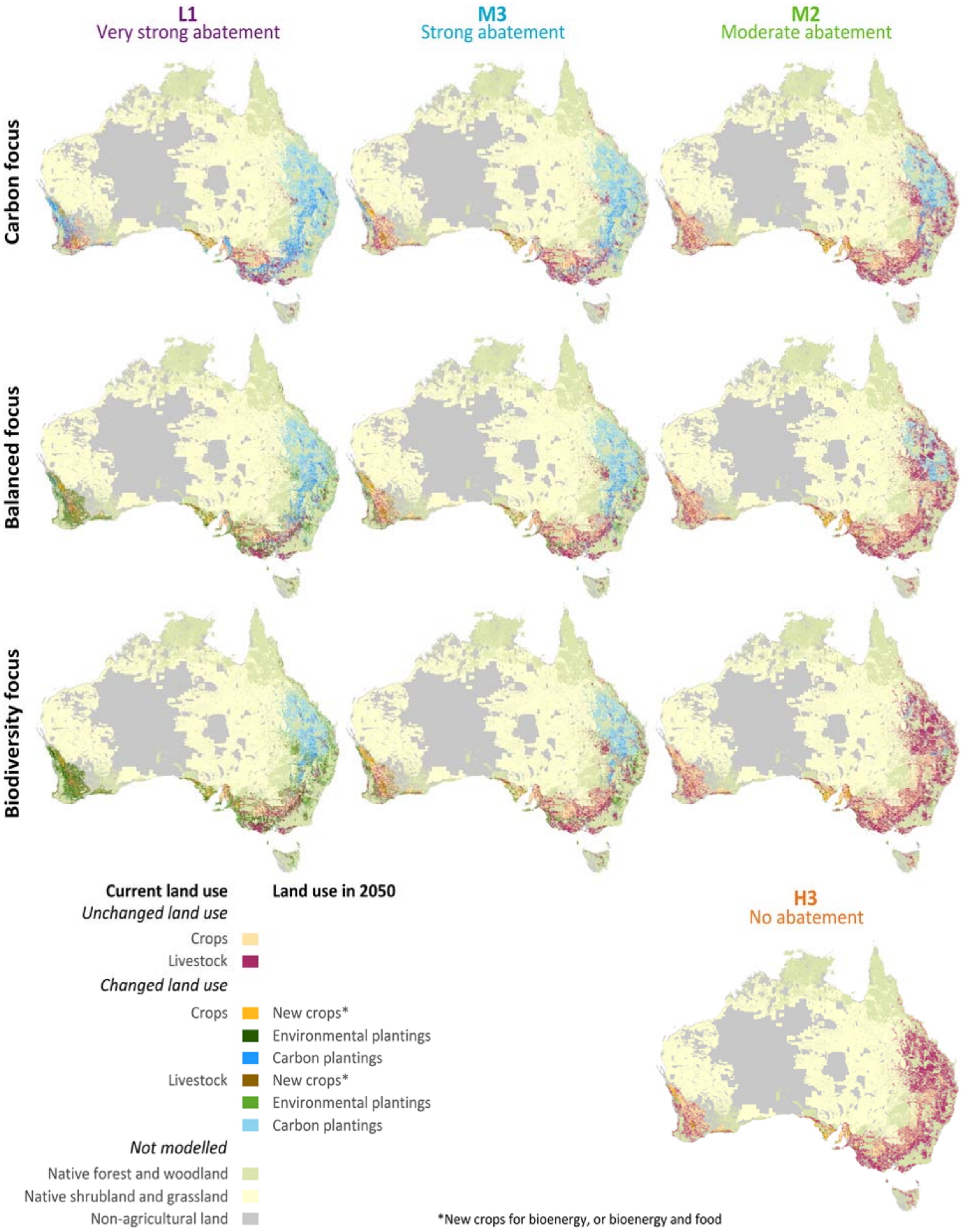


Figure A.2. Location of new most profitable land uses across different global scenarios and biodiversity payment schemes at 2050 (modelled for the intensive use zone) for the ANO scenario

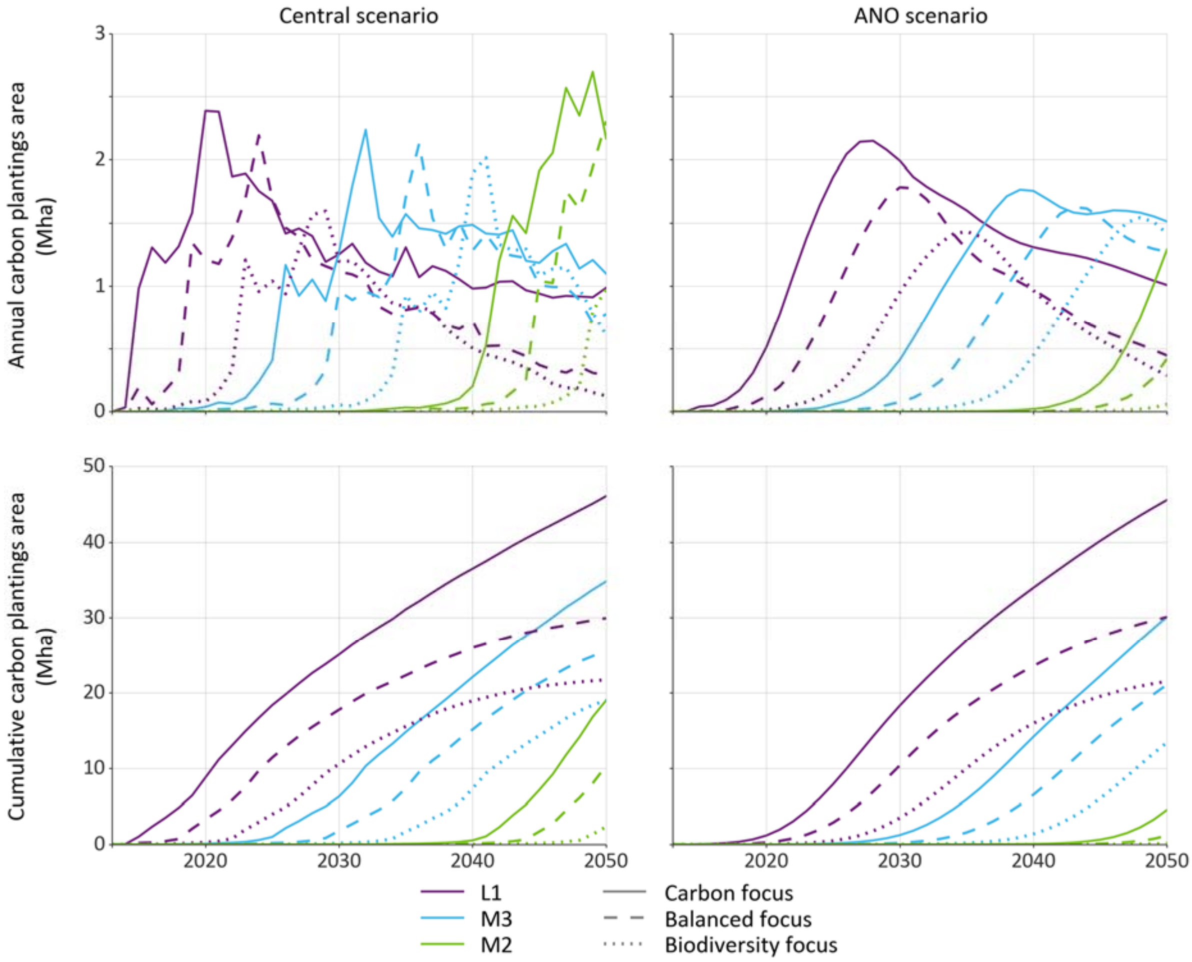


Figure A.3. Annual and cumulative carbon plantings area for the central scenario (left) and the ANO scenario (right)

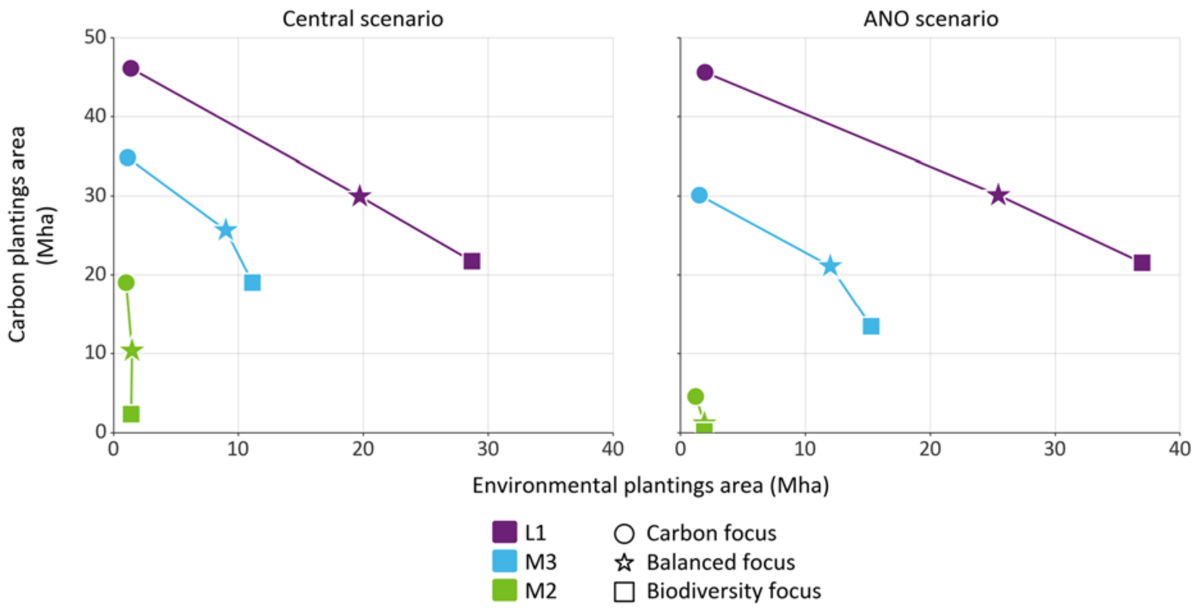


Figure A.4. Carbon plantings – environmental plantings area trade-offs for three global scenarios at different biodiversity policy settings for the central scenario (left) and the ANO scenario (right) at 2050

Acronyms

ACRONYM	DEFINITION
ANO	Australian National Outlook
AUD	Australian dollars
°C	Degrees Celsius
CO_2	Carbon dioxide
GDP	Gross domestic product
GIAM	Global Integrated Assessment Model
GL	Gigalitre
Gt	Gigatonne
ha	Hectare
LUTO	Land Use Trade-Offs
Mha	Million hectares
ML	Megalitre
Mt	Megatonne
PJ	Petajoule
t	Tonne
TL	Teralitre
Tpc	Total particulate carbon

References

Australian Government – Department of the Environment (2015) *Permanence*. *http://www.environment.gov.au/climate-change/emissions-reduction-und/cfi/permanence* last accessed 1.4.15.

Australian Government – Department of the Sustainability, Environment, Water, Population and Communities (2015) *Biodiversity Fund Round Two: 2013–14 grant application guidelines*. *http://www.environment.gov.au/cleanenergyfuture/biodiversity-fund/round-2/pubs/round-two-guidelines.pdf*

Bryan B, Nolan M, Harwood T, Connor J, Navarro-Garcia J, King D, Summers D, Newth D, Cai Y, Grigg N, Harman I, Crossman N, Grundy M, Finnigan J, Ferrier S, Williams K, Wilson K, Law E and Hatfield-Dodds S (2014) Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. *Global Environmental Change* 28, 166–181.

Bryan BA and Crossman ND (2013) Impact of multiple interacting financial incentives on land use change and the supply of ecosystem services. *Ecosystem Services* 4, 60–72.

Bryan BA, Crossman ND, Li J, Nolan M, Navarro-Garcia J and Connor JD (2015) Land use efficiency: anticipating future demand for land-sector greenhouse gas emissions abatement and managing trade-offs with agriculture, water, and biodiversity. *Global Change Biology.*

Bryan BA, King D and Ward JR (2011) Modelling and mapping agricultural opportunity costs to guide landscape planning for natural resource management. *Ecological Indicators* 11, 199–208.

Bryan BA, Nolan M, McKellar L, Connor JD, Newth D, Harwood T, King D, Navarro J, Gao L, Grundy MJ, Graham P, Ernst A, Dunstall S, Stock F, Brinsmead T, Harman I, Grigg NJ, Battaglia M, Keating B, Wonhas A and Hatfield-Dodds S (under review) *Land use and sustainability under intersecting global change and domestic policy scenarios: trajectories for Australia to 2050.*

Bullard SH, Gunter JE, Doolittle ML and Arano KG (2002) Discount rates for nonindustrial private forest landowners in Mississippi: How high a hurdle? *Southern Journal of Applied Forestry* 26, 26–31.

Burns K, Hug B, Lawson K, Ahammad H and Zhang K (2011). *Abatement potential from reforestation under selected carbon price scenarios,* ABARES Special Report. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Cai Y, Newth D, Finnigan J and Gunasekera D (2015) A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation. *Applied Energy* 148, 381–395.

ClimateWorks Australia, ANU, CSIRO and CoPS (2014) *Pathways to Deep Decarbonisation in 2050: How Australia can prosper in a low carbon world: Technical report*. ClimateWorks Australia.

Connor JD, Bryan BA, Nolan M, Stock F, Dunstall S, Graham P, Ernst A, Newth D, Grundy M and Hatfield-Dodds S (2015) Modeling continental land use change and ecosystem services with market feedbacks at high spatial resolution. *Environmental Modelling and Software* 69, 141–154.

DCCEE (2011) *Securing a clean energy future: the Australian Government's climate change plan*. Canberra, Australia: Department of Climate Change and Energy Efficiency, Commonwealth of Australia, Canberra.

Dumortier J (2013) *The effects of uncertainty under a cap-and-trade policy on afforestation in the United States*. Environmental Research Letters 8, 044020.

Eady S, Grundy M, Battaglia M and Keating B (eds.) (2009) *An Analysis of Greenhouse Gas Mitigation and Carbon Sequestration Opportunities from Rural Land Use*. CSIRO, Brisbane.

Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N, Le Quéré C, Raupach MR, Sharifi A, Smith P and Yamagata Y (2014) Betting on negative emissions. *Nature Climate Change* 4, 850–85.

Garnaut, R (2008) *The Garnaut Climate Change Review: Final Report*. Cambridge University Press, Port Melbourne.

Gray EM, Sheng Y, Oss-Emer M and Davidson A (2012) Agricultural Productivity: Trends and policies for growth. *Agricultural Commodities* 2(1), 166–179.

Grundy MJ, Bryan BA, Nolan M, Connor JD, Hatfield-Dodds S, Keating BA and Battaglia M. (in review) *Scenarios for Australian agricultural production and land use to 2050.* Working paper of the CSIRO National Outlook 2014, Canberra.

Hatfield-Dodds S, McKellar L, Brinsmead TS, Bryan BA, Graham P, Grundy M.J, Harwood T, Newth D, Schandl H, Wonhas A, Adams P, Cai Y, Ferrier S, Finnigan J, McCallum R, Nolan M, Prosser I, Stafford Smith M, Battaglia M, Baynes T, Chiew F, Connor J, Geschke A, Grigg N, Harman I, Hayward J, Keating B, King D, Lenzen M, Lonsdale M, McCrea R, Navarro Garcia J, Owen A, Raison J, Reedman L, Smith MH, Summers D and Whetton P (2015) *Australian National Outlook 2015 – Technical Report: Economic activity, resource use, environmental performance and living standards, 1970–2050,* CSIRO, Canberra.

Lawson K, Burn K, Low K, Heyhoe E and Ahammad H (2008) *Analysing the economic potential of forestry for carbon sequestration under alternative carbon price paths*. Australian Bureau of Agricultural and Resources Economics, Canberra.

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M and Kram T (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463, 747–756.

Mpelasoka F, Hennessy K, Jones R and Bates B (2008) Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management. *International Journal of Climatology* 28, 1283–1292.

Murray-Rust D, Rieser V, Robinson DT, Milicic V and Rounsevell M (2013) Agent-based modelling of land use dynamics and residential quality of life for future scenarios. *Environmental Modelling and Software* 46, 75–89.

National Water Commission (2012) *Assessing water stress in Australian catchments and aquifers.* Australian Government, Australian Government, Canberra.

Nossal K and Sheng Y (2010) Productivity growth: trends, drivers and opportunities for broadacre and dairy industries. *Australian Commodities* 17, 216–230.

Polglase P (2009) Change land use to carbon forestry. In: Eady S, Grundy M, Battaglia M and Keating B (eds.) (2009) *An Analysis of Greenhouse Gas Mitigation and Carbon Sequestration Opportunities from Rural Land Use*. CSIRO, Brisbane.

Polglase P J, Reeson A, Hawkins C S, Paul K I, Siggins A W, Turner J, Crawford DF, Jovanovic T, Hobbs T J, Opie K, Carwardine J and Almeida A (2013) Potential for forest carbon plantings to offset greenhouse emissions in Australia: economics and constraints to implementation. *Climatic Change* 121 (2), 161–175.

Polglase P, Paul K, Hawkin C, Siggins A, Turner J, Booth T, Crawford D, Jovanovic T, Hobbs T, Opie K, Almeida A and Carter J (2008) *Regional Opportunities for Agroforestry Systems in Australia*. RIRDC Publication No. 08/176, October 2008, Canberra.

Prestemon JP and Wear DN (2000) Linking harvest choices to timber supply. *Forest Science* 46, 377–389.

Rogelj J, Meinshausen M and Knutti R (2012) Global warming under old and new scenarios using IPCC climate sensitivity range estimates*.* *Nature Climate Change*, published online: 5 February 2012, DOI: 10.1038/NCLIMATE1385

Rogers E (2003) *Diffusion of Innovations*, Free Press, New York.

Schroter D, Cramer W, Leemans R, Prentice IC, Araujo MB, Arnell NW, Bondeau A, Bugmann H, Carter TR, Gracia CA, de la Vega-Leinert AC, Erhard M, Ewert F, Glendining M, House JI, Kankaanpaa S, Klein RJT, Lavorel S, Lindner M, Metzger MJ, Meyer J, Mitchell TD, Reginster I, Rounsevell M, Sabate S, Sitch S, Smith B, Smith J, Smith P, Sykes MT, Thonicke K, Thuiller W, Tuck G, Zaehle S and Zierl B (2005) Ecosystem service supply and vulnerability to global change in Europe. *Science* 310, 1333–1337.

The Treasury (2011) *Strong Growth, Low Pollution – Modelling a Carbon Price*. The Commonwealth of Australia, Canberra.

The Treasury (Department of the Treasury) and the Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education (2013) *Climate Change Mitigation Scenarios Modelling report provided to the Climate Change Authority in support of its Caps and Targets Review*, Canberra.

United Nations (UN), Department of Economic and Social Affairs, Population Division (2013) *World Population Prospects: The 2012 Revision, Key Findings and Advance Tables.* United Nations, New York, USA.

van Dijk AIJM (2010) *The Australian Water Resources Assessment System. Technical Report 3. Landscape Model (version 0.5) Technical Description.* CSIRO Water for a Healthy Country National Research Flagship.

van Dijk AIJM and Renzullo LJ (2011) Water resource monitoring systems and the role of satellite observations*. HESS* 15, 39–55.

van Vuuren D, Edmonds J, Kainuma M, Riahi K and Thomson A (2011) The representative concentration pathways: an overview. *Climatic Change* 109, 5–31.

Whitten SM and Coggan A (2013) Market based instruments and ecosystem services: opportunity and experience to date. In Wratten, S., Sanhu, H., Cullen, R. and Costanza, R. (eds.). *Ecosystem Services in Agricultural and Urban Landscapes*. Wiley-Blackwell, Chichester

Zhang L, Dawes WR and Walker GR (2001) Response of Mean Annual Evapotranspiration to Vegetation changes at Catchment Scale. *Water Resources Research* 37, 701–708.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

FOR FURTHER INFORMATION

Steve Hatfield-Dodds
t +61 2 6246 5597
e steve.hatfield-dodds@csiro.au
w www.csiro.au/