Land-use and sustainability under intersecting global change and domestic policy scenarios: trajectories for Australia to 2050

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Land-use and sustainability under intersecting global change and domestic policy scenarios: Trajectories for Australia to 2050

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ABSTRACT

Understanding potential future influence of environmental, economic, and social drivers on land-use and sustainability is critical for guiding strategic decisions that can help nations adapt to change, anticipate opportunities, and cope with surprises. Using the Land-Use Trade-Offs (LUTO) model, we undertook a comprehensive, detailed, integrated, and quantitative scenario analysis of land-use and sustainability for Australia's agricultural land from 2013–2050, under interacting global change and domestic policies, and considering key uncertainties. We assessed land use competition between multiple land-uses and assessed the sustainability of economic returns and ecosystem services at high spatial (1.1 km grid cells) and temporal (annual) resolution. We found substantial potential for land-use transition from agriculture to carbon plantings, environmental plantings, and biofuels cropping under certain scenarios, with impacts on the sustainability of economic returns and ecosystem services including food/fibre production, emissions abatement, water resource use, biodiversity services, and energy production. However, the type, magnitude, timing, and location of land-use responses and their impacts were highly dependent on scenario parameter assumptions including global outlook and emissions abatement effort, domestic land-use policy settings, land-use change adoption behaviour, productivity growth, and capacity constraints. With strong global abatement incentives complemented by biodiversity-focussed domestic land-use policy, land-use responses can substantially increase and diversify economic returns to land and produce a much wider range of ecosystem services such as emissions abatement, biodiversity, and energy, without major impacts on agricultural production. However, better governance is needed for managing potentially significant water resource impacts. The results have wide-ranging implications for land-use and sustainability policy and governance at global and domestic scales and can inform strategic thinking and decision-making about land-use and sustainability in Australia. A comprehensive and freely available 26 GB data pack (http://doi.org/10.4225/08/5604A2E8A00CC) provides a unique resource for further research. As similarly nuanced transformational change is also possible elsewhere, our template for comprehensive, integrated, quantitative, and high resolution scenario analysis can support other nations in strategic thinking and decision-making to prepare for an uncertain future.

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1. Introduction

Influential drivers of land-use such as climate, population, policy, market forces, technology, affluence, and societal preferences, will change rapidly over the next few decades (Gerland et al., 2014; IPCC, 2013; Newell et al., 2014), potentially transforming the use and management of land (Bryan et al., 2013; Wise et al., 2009). Understanding potential future changes in these drivers and their effect on land-use and sustainability across space and over time is critical for guiding strategic decisions that can help nations adapt to change, anticipate opportunities, avoid disasters, and cope with surprises (Bateman et al., 2013; Miller and Morisette, 2014). However, operating at multiple spatial and temporal scales within complex social-ecological systems, these drivers are characterised by non-linear dynamics such as dependencies, thresholds, and feedbacks (Liu et al., 2007). Hence, their trajectories can be volatile, uncertain, and even ambiguous (Chermack, 2011), and their influence on land-use and sustainability is complex, often characterised by synergies and trade-offs (Bryan, 2013; Bryan et al., 2011a; DeFries et al., 2004; Lambin and Meyfroidt, 2010; Parrott and Meyer, 2012). This multiscale, layered, and interacting complexity and uncertainty renders long-run outcomes for land systems deeply uncertain and far beyond the reach of scientific tools designed for predictive forecasting, as opposed to exploratory projection (Alcamo, 2008; Kates et al., 2001; Parker et al., 2008; Zurek and Henrichs, 2007).

Scenario analysis has emerged over the past half-century as a methodology for analysing deeply uncertain, long-run future sustainability pathways for complex social-ecological systems to support strategic decision-making (Kates et al., 2001; Schoemaker, 2004; Swart et al., 2004). As 'plausible descriptions of how the future may develop based on a coherent and internally-consistent set of assumptions about key relationships and driving forces' (IPCC, 2000; Millennium Ecosystem Assessment, 2005), scenarios are archetypes containing multiple interacting uncertainties (Schoemaker, 2004). Scenario analysis is particularly useful for assessing long-run sustainability as it provides an interdisciplinary framework that anticipates diverse possibilities, incorporates multiscale spatial and temporal processes, embraces system complexity and uncertainty, integrates disparate issues, accounts for human volition, combines qualitative and quantitative data, and engages stakeholders (Swart et al., 2004). Land-use and sustainability scenario analysis can support environmental governance and policy-making by increasing our understanding of: the possible outcomes of taking no action (i.e. business as usual); the effectiveness of alternative policy designs; the likelihood of achieving environmental targets; the robustness of policy options under future uncertainty; and the long-term outcomes of policy including synergies, trade-offs, surprises, and perverse outcomes (Alcamo, 2008).

Quantitative scenario analysis underpinned by data-centric modelling has been widely applied at multiple scales and has addressed multiple issues to support evidence-based strategic policy for sustainability (Alcamo et al., 2008; Heistermann et al., 2006; Rothman, 2008; Rounsevell et al., 2014, 2012a). Global scenario analyses (IPCC, 2000; Meadows et al., 1972; Millennium Ecosystem Assessment, 2005; Moss et al., 2010; Nakicenovic et al., 2014; Raskin, 2005; UNEP, 2012) have typically employed integrated assessment models to quantify key environmental and economic parameters (Eickhout et al., 2007; Krey, 2014; Stehfest et al., 2014). Some global models have included enhanced sectoral detail for agriculture and land-use (Golub et al., 2012; Havlik et al., 2011; Lotze-Campen et al., 2008; Rosengrant and The IMPACT Development Team, 2012; Thomson et al., 2010; van der Werf and Peterson, 2009; Wise et al., 2009). However, the land system dynamics in these models operate at spatial and/or temporal resolutions far below that required to address many aspects of land system sustainability such as economic returns to land, food/fibre production, water resources, biodiversity, soils, energy, emissions, and other ecosystem services (Connor et al., 2015; Dong et al., 2015; Rounsevell et al., 2014; Verburg et al., 2012, 2013).

Top-down or *inductive* (Overmars et al., 2007) approaches to land system scenario analyses have downscaled and spatially-allocated broad land sector outputs from global models at high resolution based on pixel-level geographical suitability (Letourneau et al., 2012; Mancosu et al., 2015; Rounsevell et al., 2005; Schaldach et al., 2011; Sleeter et al., 2012; Sohl et al., 2014; Swetnam et al., 2011; Van Asselen and Verburg, 2013; Verburg et al., 2008, 2006, 2010; Verburg and Overmars, 2009). Overwhelmingly, these studies have focussed on the area and spatial configuration of land-use change. While these downscaled land-use change projections have been used to quantify aspects of land system sustainability such as carbon sequestration (Schulp et al., 2008), biodiversity (Sohl et al., 2014), and ecosystem services (Brown and Castellazzi, 2014; Schroter et al., 2005; Verburg et al., 2012), the timing of land-use change and its impacts on sustainability has not been widely assessed. Advantages of top-down approaches to future land system sustainability assessment include a strong connection to quantitative global change scenarios and a strong empirical basis for spatial allocation of land-use change. However, they are typically limited to the analysis of marginal change and lack the flexibility to incorporate new land-uses in response to new policies and market opportunities (Overmars et al., 2007). Further challenges include incorporating other effects such as national and local level social, economic, and policy drivers; non-stationarity in correlates of land-use change; non-linearity in key drivers over time; transformational impacts of out-of-sample conditions, and; feedbacks from changes in supply/demand or diminishing marginal returns.

Bottom-up or *deductive* (Overmars et al., 2007) approaches, broadly classed as econometric, agent-based, and systems models have also been widely used to project future land-use change and evaluate sustainability indicators at high resolution. Econometric models have been used to estimate statistical relationships between land-use and geographic/economic variables and to simulate future responses of land-use to policy (Antle and Capalbo, 2001; Plantinga, 2015; Radeloff et al., 2012). Sustainability impacts have been quantified via linked biophysical models using indicators of biodiversity (Beaudry et al., 2013; Lewis, 2010), carbon sequestration (Busch et al., 2012; Lubowski et al., 2006), and multiple ecosystem services (Lawler et al., 2014; Nelson et al., 2008). While bottom-up econometric models have proven effective for analysing policy impacts, they have not been strongly connected to quantitative global change scenarios, and they share many of the limitations of top-down models.

Agent-based and systems dynamics approaches are flexible, integrated, mechanistic models that simulate the linked biophysical, economic, and human behavioural processes of land-use change over space and time. They can capture the influence of changes in quantitative scenario drivers, as well as policy and management intervention (Hamilton et al., 2015; Rounsevell et al., 2012a). These models can incorporate the complexity of land-use and sustainability including non-linear and non-stationary processes, multiscale effects, and transformational change. Agent-based models have been widely used to project land-use change, with some addressing aspects of sustainability (Schreinemachers and Berger, 2011), and global change (Guillem et al., 2015). While they have traditionally focused on detailed but localised human behaviour and decision-making in response to change in environmental, economic, and policy drivers (Guillem et al.,

2015; Parker et al., 2003), recent developments show potential for global application (Arneth et al., 2014; Rounsevell et al., 2012b).

Systems models, which can be more readily applied at scale, hold great potential for addressing the complexity and uncertainty challenges in assessing long-run sustainability in land systems (Antle and Valdivia, 2006). Systems models can be strongly linked to quantitative global scenarios by taking estimates of key drivers as inputs into simulations of land-use change over time and space (Busch, 2006), with sustainability outcomes calculated via linkage to biophysical models. Most applications have occurred at catchment scale (Antle and Valdivia, 2006; Bohnet et al., 2011; Crossman et al., 2012; Luo et al., 2005; Summers et al., 2012, 2015a). For example, Briner et al. (Briner et al., 2012, 2013) combined a crop model, forest growth model, and a profit-maximising land allocation model to estimate competition between forest and agriculture and the trade-offs for ecosystem services under climatic and socio-economic scenarios to 2080 for the Visp valley in Switzerland. In the Lower Murray region of southern Australia, significant economic potential for land transition from agriculture to bioenergy (Bryan et al., 2010b), biofuels (Bryan et al., 2010a), and other land-use and management options (Bryan et al., 2011a) was found in response to future climate, economic, and policy drivers. At the continental-scale however, examples are scarcer. Audsley et al. (2006) linked a crop model and farm economic model to estimate land-use change based at high resolution for Europe and the impacts for agricultural production and economic returns under quantitative climatic and socio-

economic change associated with four global scenarios to 2050. Substantial potential for supply of carbon sequestration and biodiversity services from reforestation in Australia's agricultural land was found given a global carbon price and national biodiversity payment scheme under global change, analysed at high spatial and temporal resolution (Bryan et al., 2014b). Further advances in continental-scale systems analyses are required to better inform strategic national decisions for long-run land system sustainability, specifically in assessing: high resolution trends over time as well as space; multiple potential land-use options; multiple indicators of environmental and economic sustainability, and; intersecting global and domestic policy responses.

In this study, we quantified the impact of potential long-run future scenarios combining global outlooks of environmental and economic change with domestic policy measures addressing high priority environmental issues, on Australian land-use and its economic and environmental sustainability. Via innovation in integrated, bottom-up systems modelling we quantified continental-scale, long-run future trends for Australian land-use and sustainability at high spatial and temporal resolution from 2013 to 2050. For four global outlooks specified within CSIRO's Australian National Outlook (Hatfield-Dodds et al., 2015a), trajectories in the key land-use drivers—climate; prices for carbon, oil, and electricity; and demand for crops and livestock—were quantified with the Global Integrated Assessment Model (GIAM; Newth et al., 2013) and the Energy Sector Model (ESM; Graham, 2013; Reedman and Graham, 2013) over time, ensuring internal consistency.
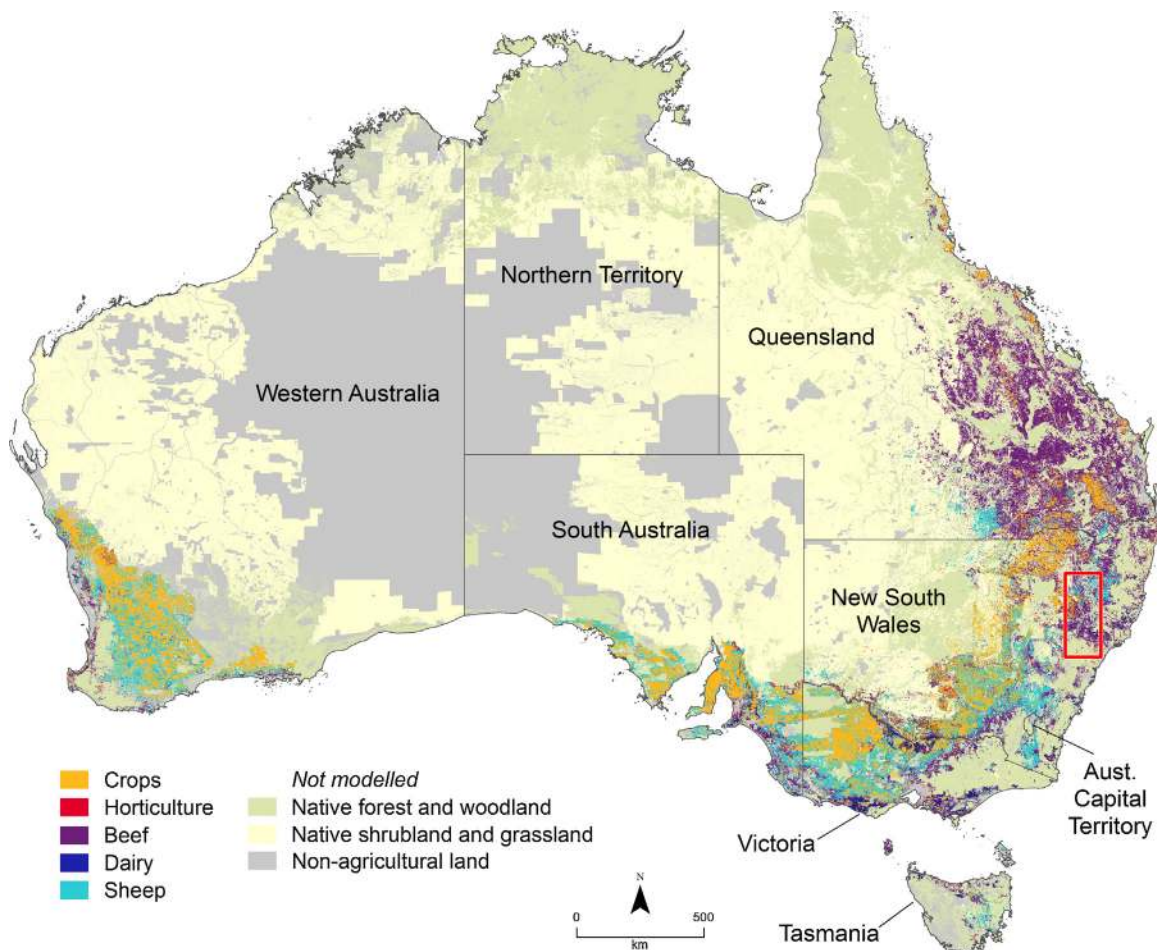
Fig. 1. Broad agricultural land-use in the study area including the location of the area of interest (red box) shown in Fig. 8. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Superimposed were two domestic policy drivers—a land-use payment policy that shifted the focus of carbon incentives to include biodiversity objectives, and a biofuels/bioenergy policy. These drivers formed key inputs into the Land-use Trade-Offs (LUTO) model (Bryan et al., 2014b; Connor et al., 2015) which identified the potential outcomes of economic competition between agriculture and a range of new reforestation (i.e. carbon plantings, environmental plantings, woody perennials), biofuels, and bioenergy land-uses under future environmental, economic, and policy scenarios. We then calculated the impact over time of potential land-use change on six sustainability indicators—economic returns to land, food/fibre production, greenhouse gas emissions abatement, water resource use, biodiversity services, and energy production. We quantified the impact of key uncertainties identified via global sensitivity analysis (Gao et al., 2016), namely productivity growth, land-use change adoption behaviour, capacity constraints on land-use change, and choice of general circulation (climate) model (GCM). The results provide a timely contribution to a number of intersecting national issues including land-based greenhouse gas abatement, development of northern Australia, water resource management, agricultural productivity, and regional development. Spatial and temporal data products from the full set of 648 Australian land-use scenarios are freely available for download (Bryan et al., 2015b). Together, this comprehensive synthesis of long-run land system sustainability and the accompanying data set provide a basis for informed national strategic decision-making in Australia, a resource for further research, and a template for other nations and continents.

2. Methods

2.1. Study area

Our 85.3 million hectare study area incorporated the intensive agricultural land of Australia (a non-contiguous area from south-western Western Australia to eastern Queensland; Fig. 1). We considered only cleared agricultural land and excluded other land-uses such as urban land, water bodies, and forest and woodland. Around 60% of Australian agricultural production is exported,

Table 1
Agricultural commodities considered in the LUTO model and their area of production (ABARES, 2010; Australian Bureau of Statistics, 2006).

Agricultural commodities	Area in 2006 (kha)	
	Dryland	Irrigated
Winter cereals	17,990.4	172.6
Summer cereals	734.7	94.6
Rice	0.0	101.8
Winter legumes	1,696.2	7.2
Summer legumes	24.7	9.0
Winter oilseeds	976.8	10.5
Summer oilseeds	64.7	12.1
Sugarcane	281.4	204.3
Pastures and crops for hay	1,618.8	269.6
Cotton	55.7	271.3
Other non-cereal crops	1.1	2.1
Vegetables	11.4	114.1
Apples	4.2	8.1
Pears and other pome fruit	1.2	3.4
Stone fruit excluding tropical	11.1	43.9
Tropical stone fruit	4.7	11.6
Nuts	12.7	15.3
Plantation fruit	9.5	9.4
Grapes	25.0	138.1
Citrus	7.1	43.4
Dairy	2,019.5	715.4
Beef	32,491.6	123.9
Sheep	18,443.7	5.0

making the region a globally significant contributor to food security. Land-use in the study area is diverse (Table 1) with dryland agriculture (mixed grazing, cropping) dominating agricultural land-use, punctuated by localised areas of high-value irrigation (ABARES, 2010; Australian Bureau of Statistics, 2006; Bryan et al., 2009a; Marinoni et al., 2012). Climate ranges from cool-temperate and Mediterranean in the south to semi-arid in the interior and sub-tropical in the north.

2.2. Overview of the LUTO model

We used LUTO—an integrated, environmental-economic model of land systems—to project potential land-use and ecosystem services under intersecting global change and domestic policy combinations for Australia. LUTO has been widely used to model specific land-use change and sustainability issues in Australia including biodiversity and carbon policy (Bryan et al., 2014b; Bryan et al., 2016), water resource policy (Connor et al., in review), agriculture and food security (Grundy et al., 2016), and trade-offs between ecosystem services (Bryan et al., 2015a). Below we provide only a summary of the LUTO model and its parameterization as the full technical detail has been published elsewhere, including several papers describing creation of the underpinning data (e.g. Bryan et al., 2014b; Navarro et al., 2016), a full description and evaluation of the land-use allocation algorithm (Connor et al., 2015), and sensitivity analyses of model parameters (Dong et al., 2015; Gao and Bryan, 2016; Gao et al., 2016).

LUTO is implemented as a constrained, partial equilibrium, linear mathematical programming model which integrates multiple spatio-temporal models and data layers from a variety of sources (Table S1) and aims to maximise the sum of consumer and producer surplus from land-use. Here, we assessed 648 (i.e. $4 \times 3 \times 3 \times 3 \times 3 \times 2$) combinations of global outlooks (4), domestic policies (3), and key uncertainties ($3 \times 3 \times 3 \times 2$) at an annual time step and spatial resolution of ~1.1 km (0.01°) grid cells (consistent with the land use mapping resolution) for the 38 years from 2013 to 2050 (Fig. 2). The model starts with a base map of current agricultural land-use (Fig. 1 and Table 1). In each grid cell, for each year, the choice is whether to continue with current agriculture (Table 1), or to change to a new land-use (Table 2), noting that due to the existence of widespread regulatory controls on land clearance (at the time of modelling), agriculture does not expand into remnant natural areas. Economic returns to new land-uses were first calculated based on revenues and costs, given the influence of exogenous settings for rainfall, temperature, and run-off; prices for carbon, petrol and oil, and electricity; productivity growth and; biodiversity payment budget.

Economic returns to agriculture were also calculated. The partial equilibrium approach determines the price of agricultural commodities endogenously in response to changes in supply and demand via a price elasticity of demand relationship (Andreyeva et al., 2010), with baseline demand calibrated to observed prices (Australian Bureau of Statistics, 2006; Marinoni et al., 2012). The dominant effect of this is that agricultural commodity prices and hence, the profitability of land still in production, increase simultaneously in response to decreasing supply driven by land-use change. Price equilibrium occurs when new land-uses no longer outcompete agriculture. Over time, agricultural commodity demand curves shift upwards following global crop and livestock demand trajectories from integrated assessment.

Each year, environmental plantings funded through cost-effectively targeted biodiversity payments via the domestic land-use policy were allocated first up to the budget constraint, which is itself a function of the value of carbon sequestered by carbon plantings in the previous year. With the remaining agricultural land open to competition, relative profitability
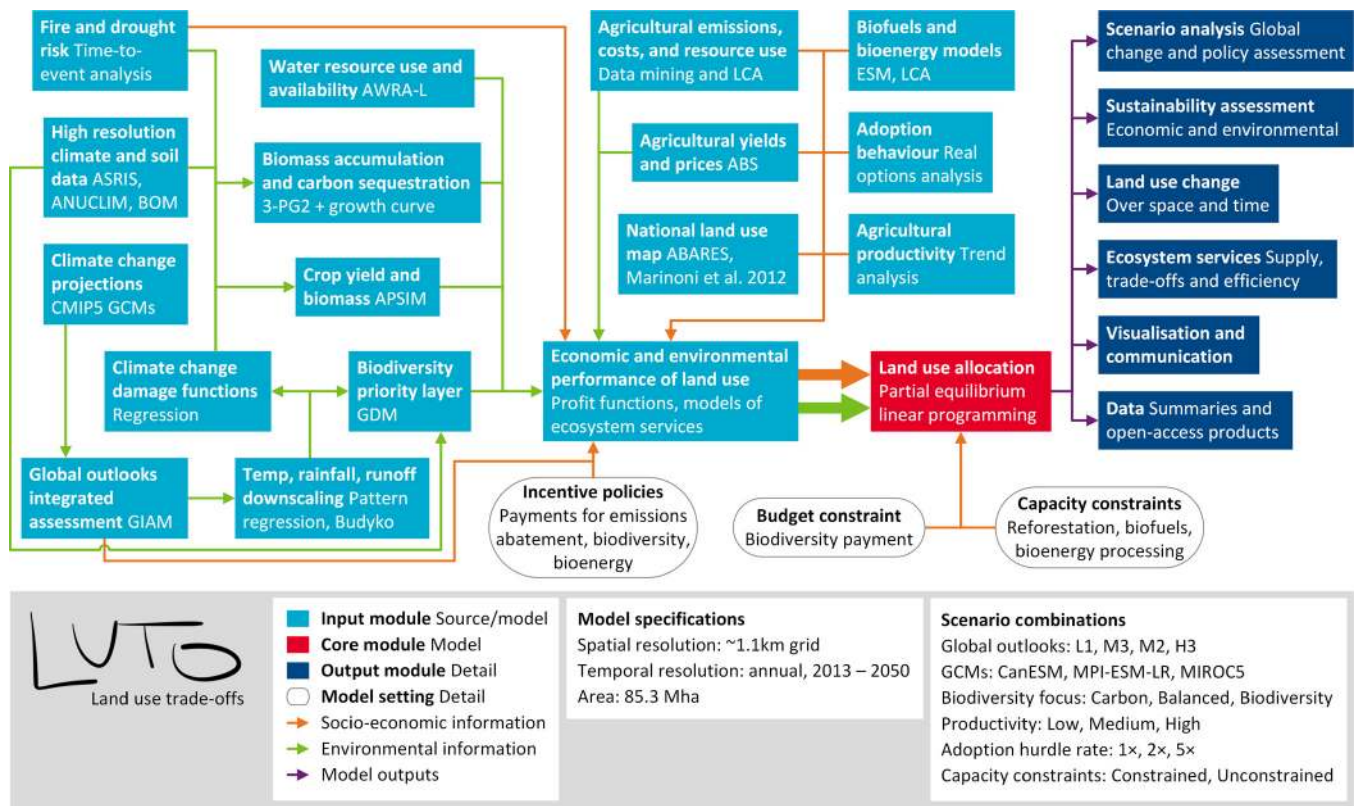
Fig. 2. Schematic structure of the LUTO model and scenario specification.

determines land-use change over space and time given adoption hurdle rate and capacity constraint settings. Capacity constraints on reforestation rates, as well as biofuels and bioenergy processing limitations, translate into reforestation area and feedstock demand constraints, respectively. LUTO's surplus maximisation objective allocates new land-uses to the most profitable grid cells within the constraint settings. Areas of crop-based biofuels and bioenergy land-uses could convert to reforestation or even revert to agriculture if it became profitable to do so, but change to reforestation-based land-uses was considered permanent.

The location and timing of potential land-use change influences economic returns and ecosystem services (Table 3). Sustainability was assessed via the seven indicators: area of land-use, economic returns to land, emissions abatement, food/fibre production, water resource use, biodiversity services, and energy production. Economic returns were calculated as the total net returns to all land-use. Emissions abatement was calculated as the sum of carbon sequestered by reforestation, the net emissions abatement achieved by biofuels and bioenergy from avoided use of fossil fuels,

and the avoided life-cycle emissions of displaced agriculture. Food/fibre production is the total value of agricultural production in 2010 Australian dollars. Water resource use is the total change in water use including increased water use by trees (surface water and groundwater) minus the water use avoided through the conversion of irrigated agriculture to other land-use. Surface water impacts were calculated as the total interception by reforestation in areas of rainfall exceeding $600\,\mathrm{mm\,yr^{-1}}$. Biodiversity services represent the benefit achieved by environmental plantings as a proportion of the total benefit possible from restoring the entire study area. Energy is the combined energy produced as ethanol and electricity from biofuels and bioenergy production. A more detailed set of 70 indicators is provided in the spreadsheet data summaries (Table S2).

2.3. Global outlooks

Global trends strongly influence Australian land-sector economic activity and land-use via climatic effects, demand for

Table 2
Description of new land-uses considered in the LUTO model.

New land-uses	Description
Carbon plantings	Monocultures of locally-selected, fast-growing, high sequestering *Eucalyptus* species
Environmental plantings	Suite of mixed, local native trees and shrubs selected to restore biodiverse native plant communities and provide habitat for local native fauna
Wheat biofuels	Wheat grain processed to produce ethanol using standard first generation fermentation processes and crop residue processed to produce ethanol using second-generation biochemical conversion processes
Wheat food/biofuels	Wheat grain sold into the food market, residue used to produce ethanol using second-generation biochemical conversion processes
Wheat food/bioenergy	Wheat grain sold into the food market, residue burned to produce renewable electricity via biomass steam generation processes
Woody perennials biofuels	Biomass from short-rotation *Eucalyptus* species used to produce ethanol using second-generation biochemical conversion processes
Woody perennials bioenergy	Biomass from short-rotation *Eucalyptus* species burned to produce renewable electricity via biomass steam generation processes

Table 3
Impact of land-use on indicators of sustainability in the LUTO model.

		Sustainability indicators					
		Economic returns	Food/fibre production	Emissions abatement	Water resources	Biodiversity services	Energy production
Land-use	Agriculture	✓	✓	✓	✓	✗	✗
	Carbon plantings	✓	✗	✓	✓	✗	✗
	Environmental plantings	✓	✗	✓	✓	✓	✗
	Wheat biofuels	✓	✗	✓	✗	✗	✓
	Wheat food/biofuels	✓	✓	✓	✗	✗	✓
	Wheat food/bioenergy	✓	✓	✓	✗	✗	✓
	Woody perennials biofuels	✓	✗	✓	✗	✗	✓
	Woody perennials bioenergy	✓	✗	✓	✓	✗	✓

agricultural goods, input costs, and incentives for emissions abatement. Hence, this analysis was contextualised within four global outlooks named L1, M3, M2, and H3. Constructed for CSIRO's Australian National Outlook (Hatfield-Dodds et al., 2015b), global outlooks are scenarios of global emissions abatement effort, climate, population, and the economy for the period 2013–2050 designed to cover a range of plausible global futures (Table 4). L (low), M (medium) and H (high) refer to the climatic warming outlook and 1 (low), 2 (mid), and 3 (high) refer to the population outlook. L1 had *very strong* emissions abatement effort, mildest climatic warming, and lowest population, whereas H3 involved *no action* to reduce global emissions, implying the strongest climatic warming. M2 and M3 represent mid-range climatic warming scenarios with M3 having *strong* abatement and high population, while M2 had *moderate* abatement with medium population (Table 4).

The Global Integrated Assessment Model (GIAM; Cai et al., 2015; Newth et al., 2013) was used to quantify future projections of prices for carbon and oil, and demand for agricultural production for input into the LUTO model (Bryan et al., 2014b; Connor et al., 2015) consistent with emissions abatement, climatic, economic, and population pathways specified in the global outlooks. GIAM combines a computable general equilibrium model of the global economy and trade (the Global Trade and Environmental Model), with a model of the global carbon cycle and climate (the Simple Carbon Climate Model, SCCM), and a model of climate-economy interactions (the MERGE model) (Newth et al., 2013). Each outlook involves settings in GIAM for four key drivers and constraints: population and labour, climate mitigation, total greenhouse gas emissions, and biosequestration. The outlooks provided a global carbon price following a Hotelling path calibrated to the cumulative emissions budgets to 2050 for the Representative Concentration Pathways (RCPs; Table 4). Trajectories for oil prices and demand for agricultural commodities consistent with these conditions were also produced in GIAM (Fig. 3). Electricity prices were provided by the Energy Sector Model (ESM)—an economic model of Australian electricity generation, transmission, and distribution; and transport fuel use (Graham, 2013; Reedman and Graham, 2013). Key inputs to ESM included global technology, and fuel and carbon prices from GIAM (Newth et al., 2013), demand for Australian electricity and transport fuel, and other parameters from the ANO modelling suite (Hatfield-Dodds et al., 2015b).

Global agricultural commodity prices were impacted by several factors including population, emissions abatement effort, and global agricultural productivity. Livestock emissions were subject to global abatement incentives and obligations in the very strong abatement outlook (L1), but not in the strong (M3) and moderate (M2) outlooks. M3, with its high population, had higher prices for crops than L1 with its low population, but L1 had higher livestock prices reflecting the impact of additional global abatement incentives and efforts to reduce livestock emissions. To provide a wider spread of agricultural price outlooks, the M2 scenario assumed higher global agricultural productivity, and so has the lowest agricultural commodity prices (Hatfield-Dodds et al., 2015b).

2.3. Domestic policy scenarios

Two main domestic policies were assessed in this study—a land-use policy and a bioenergy policy. Land-use policy was designed to adjust the domestic focus of carbon payments (from the global carbon price under global outlooks) between emissions

Table 4
Summary of the key assumptions for four global scenarios in 2050 and projected temperatures in 2100.

| Parameter	Units	2010	Global Outlook 2050			
			L1	M3	M2	H3
Climate Outlook			L	M	M	H
Temperature increase in 2100[a]	°C		1.3–1.9	2.0–3.0	2.0–3.0	4.0–6.1
Representative Concentration Pathway			3-PD	4.5	4.5	8.5
Population Outlook			1	3	2	3
Population[b]	billion people	6.9	8.1	10.6	9.3	10.6
Abatement effort			Very strong	Strong	Moderate	None
Cumulative emissions (2007–2050)[c]	Gt CO$_2$e		1437	2091	2091	2823
Emissions per capita	t CO$_2$$^{-e}$ yr^{-1}	7.0	2.2	4.7	5.4	8.7
Size of the global economy (GDP)	US$ trillion	61.0	161.6	197.0	179.1	197.8
GDP per capita	US$ thousand	8.8	20.0	18.6	19.3	18.7
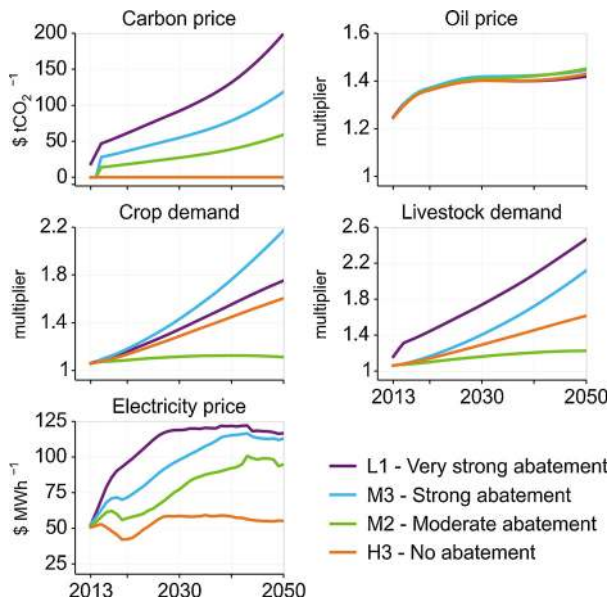
Fig. 3. Modelled trajectories for the global carbon price, price multipliers for crops, livestock, and oil, and national electricity price under the four global scenarios. © 2016 CSIRO. All rights reserved.

abatement and biodiversity conservation via a combination of targeted incentive payments for the voluntary adoption of environmental plantings in agricultural land, and a levy on carbon plantings. We assessed land-use policy under three illustrative settings: *Carbon focus*, *Balanced focus*, and *Biodiversity focus*. All three policy settings included a top-up payment for environmental plantings targeted to maximise biodiversity services per dollar of expenditure. Following other implementations (Bryan and Crossman, 2013; Bryan et al., 2014b; Crossman et al., 2011), biodiversity payments covered the net present value of the landholders' future opportunity cost (the shortfall in returns between environmental plantings and the most profitable land-use) over 100 years at current prices discounted at 10% p.a. All three policies included a baseline budget for biodiversity payments of $125 million per year (DCCEE, 2011). The *Balanced focus* and *Biodiversity focus* settings included an additional levy on carbon plantings of 15% and 30% of carbon revenue, respectively, with funds used to boost the biodiversity budget. The levy reduces the competitiveness of carbon plantings and substantially increases the budget available for environmental plantings in priority areas (Bryan et al., 2016). Bioenergy policy considered a range of distributed, small-scale biofuels (ethanol as mobile transport fuel) and bioenergy (renewable electricity) processing options using either wheat grain/residue or biomass from short-rotation woody perennials as feedstock (Table 2). Wheat food/biofuels and food/bioenergy options sold grain into the traditional food markets and the residue into biofuels and bioenergy markets, respectively. Biofuels and bioenergy land-uses received income from the energy produced but were not eligible for carbon payments.

2.4. Uncertainty dimensions

The impact of four key uncertainty dimensions (productivity growth, adoption behaviour, climate change, capacity constraints) on projections for land-use sustainability were assessed, each applied uniformly across the study area. First, three simple annual rates of productivity growth were specified for agricultural production: Low, Medium, and High. For agriculture, these were set at 0%, 1.5%, and 3.0% p.a. simple increase, respectively, based on the range of observed productivity trends over the past 35 years

(Nossal and Sheng, 2010). For carbon plantings, rates were set at 0%, 0.75%, and 1.5% p.a. simple increase, respectively, based on experience in Australian blue gum forestry plantations. These rates
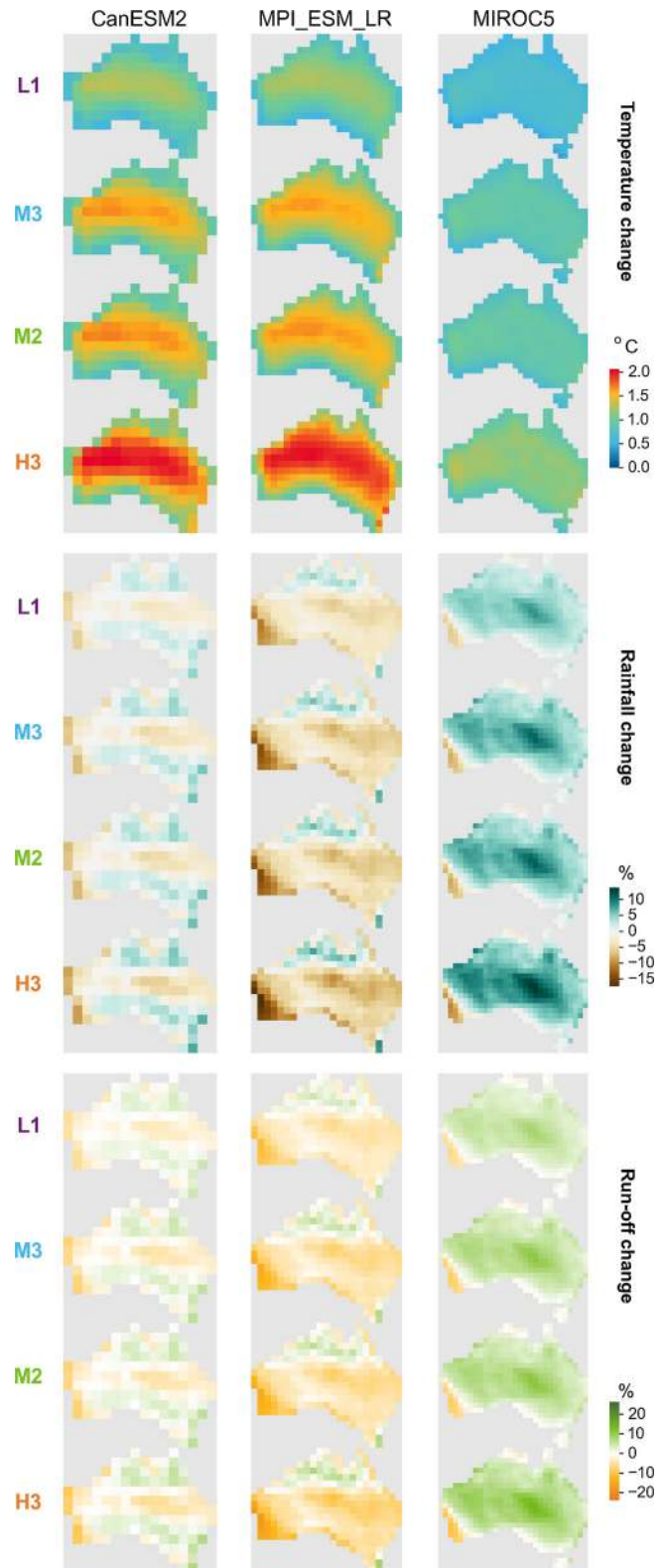
Fig. 4. Projected changes in temperature, rainfall, and run-off from 2013–2050 under the four global outlooks from the CanESM, MPI-ESM-LR, and MIROC5 GCMs (Hatfield-Dodds et al., in review). © 2016 CSIRO. All rights reserved.

depend on highly uncertain future levels of investment in research and development in agriculture and forestry.

Second, we captured uncertainty in the rate of adoption of new land-uses by landholders by specifying three adoption hurdle rates ($1 \times$, $2 \times$, $5 \times$) as profitability thresholds for determining potential land-use change. For example, under the $1 \times$ hurdle rate land-use changes when profitability of a new land-use exceeds that of agriculture. For $2 \times$ and $5 \times$, new land-uses must be more than twice, and five times, as profitable as agriculture, respectively, to be adopted. This approach captures the inertia in land-use change 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). Recent studies show that the $2 \times$ hurdle rate approximates adoption rates if option values are considered (Reeson et al., 2015; Regan et al., 2015). The $5 \times$ rate was included as a conservative bound to capture the multiple elements of risk associated with land-use change.

Third, the impact of uncertainty in future climate resulting from the emissions pathways under the four global outlooks was assessed using climate change estimates from Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs: Canadian Earth System Model (CanESM) (Chylek et al., 2011); Max Planck Institut – Earth System Model – Low Resolution (MPI-ESM-LR) (Giorgetta et al., 2013); and Model for Interdisciplinary Research on Climate version 5 (MIROC5) (Watanabe et al., 2010). These were selected to cover a range of potential climatic outcomes with CanESM being a hot, neutral-rainfall model, MPI-ESM-LR being a warm, wet, heterogeneous model, and MIROC5 being a cool, wet model (Hatfield-Dodds et al., in review). SCCM was calibrated to each GCM and used to produce mean annual, global, near-surface air temperature trajectories. Estimates of change in annual temperature and rainfall were then downscaled based on regression relationships derived from CMIP5 data (Hatfield-Dodds et al., in review). These layers then informed the calculation of run-off using the Budyko approach (Hatfield-Dodds et al., in review) (Fig. 4). Climate change layers affected many aspects of the LUTO model including agricultural productivity, tree growth, and water scarcity over space and time.

Fourth, we considered two constraint settings on the capacity for land-use change. *Unconstrained* had no limit to the rate of land-use change, assuming that a combination of private sector involvement and government support would ensure that all labour, capital, and technological requirements were met. *Constrained* imposed limitations on the rate of land-use change to the LUTO model derived from recent experience in Australia. These included a limit on reforestation informed by observed rates under a previous large-scale reforestation scheme (Polglase et al., 2013) set at 100,000 ha yr^{-1} which increased by 7% p.a. for the 10 years following the first year it was achieved, then by 10% p.a. thereafter. Biofuels feedstock was limited by processing capacity which started at 400 ML p.a. in 2013 and increased by 50ML p.a. to 2015, then by 100 ML p.a. to 2020, and by 400 ML p.a. thereafter (Graham and Smart, 2011). Bioenergy feedstock was also limited by processing capacity which started at 0.2 PJ p.a. in 2013, increasing by 2.5 PJ p.a. after 2015 (Graham and Smart, 2011).

2.5. Modelling economics and ecosystem services

A range of economic and environmental data inputs were developed for agriculture and new land-uses to underpin the calculation of economic returns, land-use change, and ecosystem service supply in the LUTO model. Much of the underpinning modelling has been published in detail elsewhere and is only summarised below with reference to more information. All dollar values were adjusted to 2010 Australian dollars and all analyses were in real terms.

A map of 2006 agricultural land-use (ABARES, 2010; Marinoni et al., 2012) provided the baseline for land-use modelling (Table 1 and Fig. 1). Yields and prices for agricultural commodities were averaged over four agricultural census years to provide long-term average values, while cost of production data was assembled from over 380 crop-and-region-specific agricultural extension handbooks (Navarro et al., 2016). Agricultural yields were adjusted over time for the impact of climate change (Fig. 4) via regression of climate and yield data from national crop modelling using the Agricultural Production Systems Simulator (APSIM; Bryan et al., 2014a, 2014b; Keating et al., 2003; Zhao et al., 2013a, 2012). Water use by irrigated agricultural crops was estimated by Marinoni et al. (2012). Life-cycle greenhouse gas emissions from agricultural crops were calculated by combining the data mining of agricultural extension handbooks and life cycle inventory data. This accounted for *cradle to farm gate* emissions from production and transport of inputs (e.g. chemicals, fodder, seed, fuel), on-farm machinery operation, but excluding emissions from machinery and infrastructure manufacturing (Navarro et al., 2016).

Estimates of growth, biomass accumulation, and carbon sequestration by carbon plantings, environmental plantings, and woody perennials were calculated using a growth curve (Zhao-gang and Feng-ri, 2003) calibrated to modelled 0.01° spatially gridded estimates for Australia (Polglase et al., 2008). Modelled growth and sequestration rates were discounted by 20% to provide a conservative buffer against the risk of overstating actual rates. Fire risk to carbon sequestration was calculated using recurrent-event regression analysis with shared frailty based on 12 years of burn scar data and simulation based on Relative Difference Normalised Burn Ratio calculated from time-series satellite imagery (Bryan et al., 2011b). Drought risk was also calculated using recurrent-event analysis based on monthly spatial Rainfall Deciles-based Drought Index data from 1970 to 2003 (Mpelasoka et al., 2008), and used to simulate the impact of drought on carbon sequestration and economic returns via plantation failure and costs of re-establishment (Bryan et al., 2011b). This implicitly assumes that the frequency of extreme events such as fire and drought will remain constant into the future, even under climate change. Annual management and transactions costs for reforestation land-uses were specified and uniformly applied over the study area (120$ ha^{-1} yr^{-1}), while establishment costs varied spatially according to the type of reforestation, soil type, topography, and other influential variables (Summers et al., 2015b).

Reforestation of crop and pasture land reduces water resource availability through increased interception and evapotranspiration by trees (Zhang et al., 2001). Water resource impacts of land-use change were estimated using the Australian Water Resources Assessment system—Landscape model (AWRA-L; van Dijk and Renzullo, 2011; van Dijk and Warren, 2010). AWRA-L combines 0.05° gridded, daily, climate data with models of catchment water balance, radiation and energy balance, vapour fluxes, and vegetation phenology, and has been calibrated to on-ground and satellite observations. We used the AWRA-L layer of difference in annual water use (ML ha^{-1}) between shallow- and deep-rooted vegetation as an estimate of water resource use by reforestation. LUTO accounts for the increased water use of new plantations by requiring the purchase of entitlements with spatially-varying costs (Burns et al., 2011) which increase with water scarcity (run-off) under climate change (Fig. 4) (Hatfield-Dodds et al., in review) via a price elasticity relationship.

Biodiversity services were calculated based on a 0.01° grid of biodiversity priority under climate change (Harwood et al., in review). The layer incorporates the principle of complementarity and representation of plant community species diversity under climate change, habitat condition, and the landscape ecological principles of connectivity and area via the species-area

relationship. Compositional dissimilarity calculated from more than 325,000 site pairs and 12,000 species, was regressed against biophysical variables using Generalised Dissimilarity Modelling (GDM; Ferrier et al., 2007), then estimated for each grid cell relative to a random sample of cells within a spatially-weighted 150 km neighbourhood. Dissimilarity was calculated under recent and 2050 climate for RCPs 4.5 and 8.5 modelled using the three GCMs. Outputs were compared and scaled to estimate the proportion of species retained in each cell under climate change (Harwood et al., in review) and combined into a single priority layer, robust to climate uncertainty, using the Limited Degree of Confidence (LDC) approach (McInerney et al., 2012). Biodiversity services were calculated as the contribution of each grid cell as a proportion of the aggregate contribution of restoring the entire study area (Bryan et al., 2015a, 2014b).

Biofuels and bioenergy production and economics were modelled using a combination of ESM (Graham, 2013; Graham et al., 2013; Graham and Smart, 2011; Reedman and Graham, 2013) and life-cycle assessment (Bryan et al., 2008, 2010a,b; Farine et al., 2012). Two types of feedstocks were considered—wheat (grain and stubble) and biomass from woody perennials (Table 2). Wheat grain was converted to biofuels using first generation processing, while wheat residue and biomass was converted using second generation lignocellulosic processing. Wheat residue and biomass were converted to renewable electricity via standard thermal generation. Farm-side economic models of feedstock production were coupled with processing-side economic models of energy generation to determine feedstock prices based on petrol and coal-fired electricity prices (Fig. 3), given a 50–50 profit share per tonne of feedstock. Wheat feedstock production volumes were calculated using the APSIM crop model which estimated annual grain yield and residual stubble biomass, based on daily climate data between 1889 and 2010 for over 11,500 homogeneous spatial units across

the study area (Bryan et al., 2014a,b; Zhao et al., 2012, 2013a). We selected a limit of 40% of the stubble biomass that could be harvested for energy production while sustaining levels of soil organic carbon (Zhao et al., 2015, 2013b). For woody biomass, trees were harvested by coppicing every 10 years, and then reshoot from rootstock. Carbon offset fractions were derived to calculate net emissions abatement achieved per tonne of feedstock production from biofuels (0.234) (SIMAPRO 7.2; Beer and Grant, 2007; Bryan et al., 2010a) and bioenergy (0.516) (AGO, 2006; Bryan et al., 2010b; Enecon, 2001) compared to petrol and coal-fired electricity, respectively, on an energy-equivalent basis. Net emissions abatement was calculated over the full life-cycle, accounting for emissions from on-farm feedstock production (diesel, fertilizer, pesticides etc.), transport, and energy generation processes. Energy production was calculated as the total energy content of the ethanol and electricity produced from biofuels and bioenergy feedstock.

The spatial distribution of net economic returns to all land-uses was quantified each year using profit functions given: a global carbon price implemented as payments per unit of emissions abatement (tCO_2^e), a targeted top-up payment for biodiversity services from environmental plantings, and a market price for biofuels and bioenergy feedstock. Profit functions have been widely used to calculate annual returns to agriculture (Bryan and Crossman, 2013; Bryan et al., 2009b, 2010a, 2011c; Hajkowicz and Young, 2005; Marinoni et al., 2012), carbon plantings and environmental plantings (Bryan et al., 2014b, 2015a; Crossman et al., 2011; Evans et al., 2015; Paterson and Bryan, 2012; Polglase et al., 2013), biofuels (Bryan et al., 2010a), and bioenergy (Bryan et al., 2010b, 2008). Following trends in carbon and energy (oil and electricity) prices, and demand for crops and livestock, profit functions were used to parameterise the calculation of economic returns to each land-use (Tables 1 and 2), each year, for each cell in
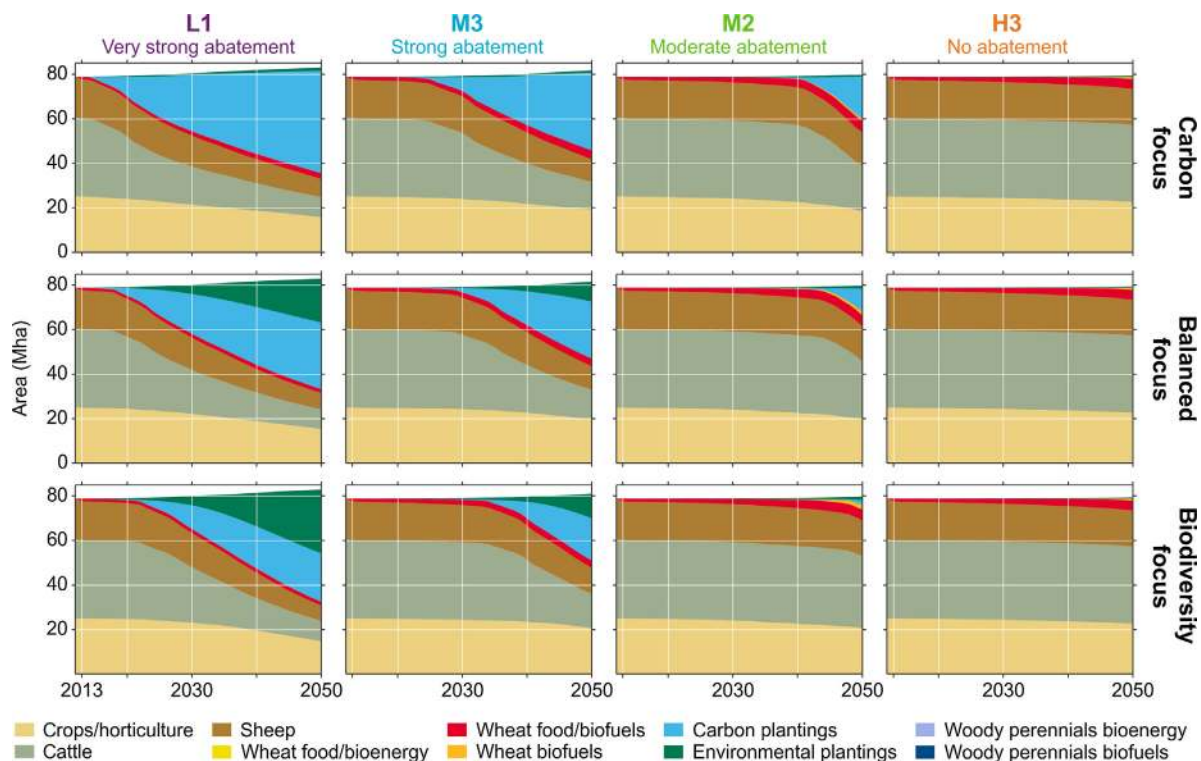
Fig. 5. Area of potential land-use change over time from 2013 to 2050 under the four global outlooks and three domestic land-use policies (Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained).

the study area. For non-reforestation land-uses, annual economic returns were calculated. For reforestation-based land-uses, economic returns were calculated in net present value terms over a rolling 100-year time horizon to smooth out the lumpy costs and revenues through time. Future returns were based on current prices and costs but included the influence of climate change on tree growth and crop yields over time. Returns were then annualised each year such that landholders received an annuity payment over 100 years, equivalent to the NPV. A constant discount rate of 10% above inflation was used to reflect the commercial returns expected from a high-risk investment.

3. Results

Here we present an illustrative subset of the results, focusing on variation across the four global outlooks and three domestic land-use policies, at the central settings for productivity growth (Medium), adoption hurdle rate (2×), GCM (MPI-ESM-LR), unconstrained. Sensitivity analysis across three productivity growth rates, three adoption hurdle rates, and two constraint settings is presented in the Supporting Information (S1 Fig–S91 Fig). Spatio-temporal data and visual outputs for the full ensemble of 648 scenarios (i.e. including the three GCMs), each modelled annually for the 38 years from 2013 to 2050, can be found online on CSIRO's Data Access Portal (Bryan et al., 2015b). These outputs include the annual land-use layers, a summary data table, a graphical dashboard summary, and an animation of potential land-use change, drivers, and impacts.

3.1. Land-use change

Under the balanced strategy (i.e. M3 Balanced focus), the total potential area of land-use transition by 2050 was 38.1 Mha (Fig. 5). Land-use transition was dominated by carbon plantings (25.7 Mha), environmental plantings (9.0 Mha), and wheat food/biofuels (3.5 Mha), with little potential for transition to woody perennials. Livestock grazing, particularly beef cattle, experienced the highest rate of land-use conversion, decreasing by 30.1 Mha (−55.9%), and crops/horticulture decreased by 5.3 Mha (−21.2%) (Fig. 6). Biofuels transition occurred early in the time horizon in the wheat/sheep areas of southern Australia, but large-scale carbon plantings did not begin until 2030 and large-scale environmental plantings did not begin until 2040. By 2050, potential for carbon plantings existed throughout the beef grazing areas of Queensland and the cropping districts of inland New South Wales. Potential for environmental plantings occurred in localised, high-priority biodiversity areas in the southern mixed-farming regions, and in Tasmania and the upland areas of New South Wales (Figs. 7–9, S1 Video–S12 Video).

Global outlooks had a strong influence on potential land-use transitions (Figs. 5 and 7, S1 Video–S12 Video). By 2050, under L1 Balanced focus, larger areas of agricultural land had potential for conversion to carbon plantings (30.0 Mha) and environmental plantings (19.7 Mha), with less biofuels cropping (1.8 Mha). Conversion was again concentrated in areas of livestock grazing which was reduced by 37.7 Mha (−70.1% from present), with crops/horticulture reduced by 9.7 Mha (−38.6%) (Fig. 6). Transitions occurred earlier than under M3, with major change to carbon
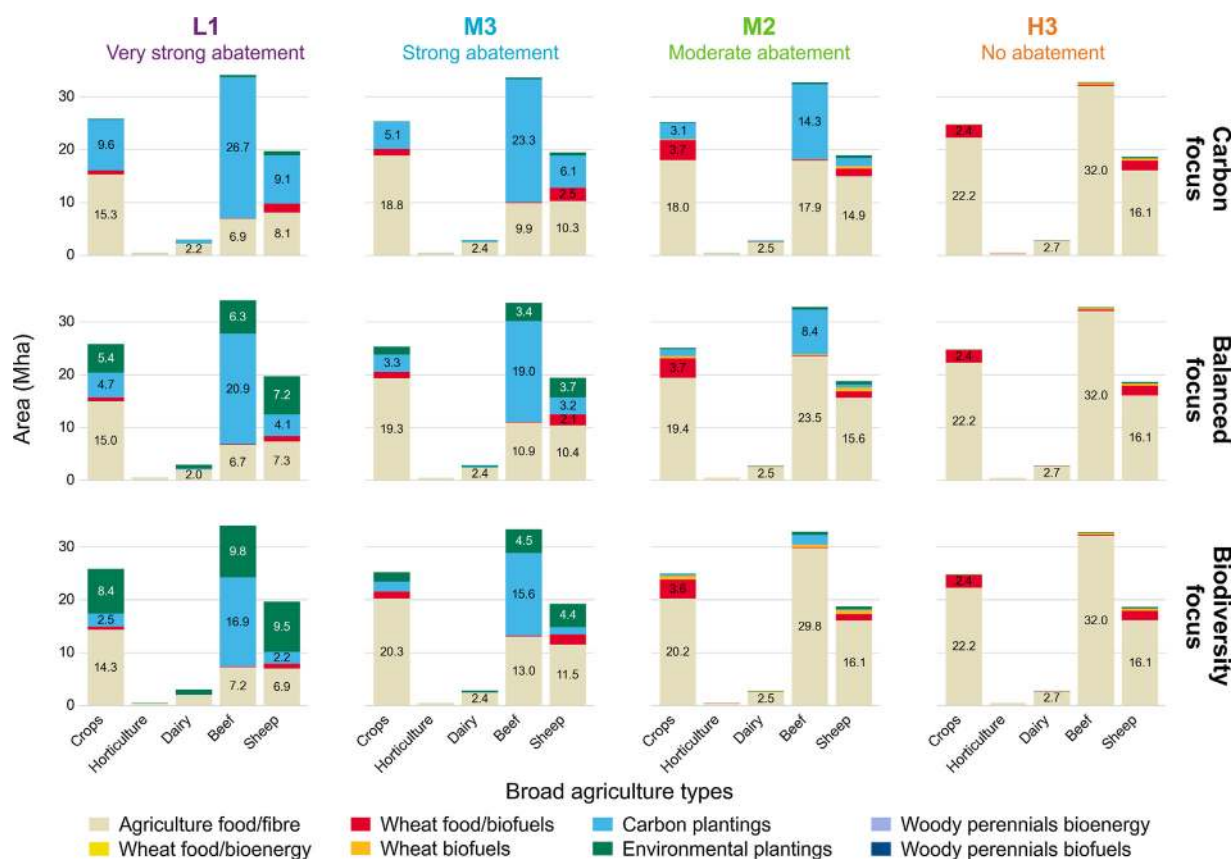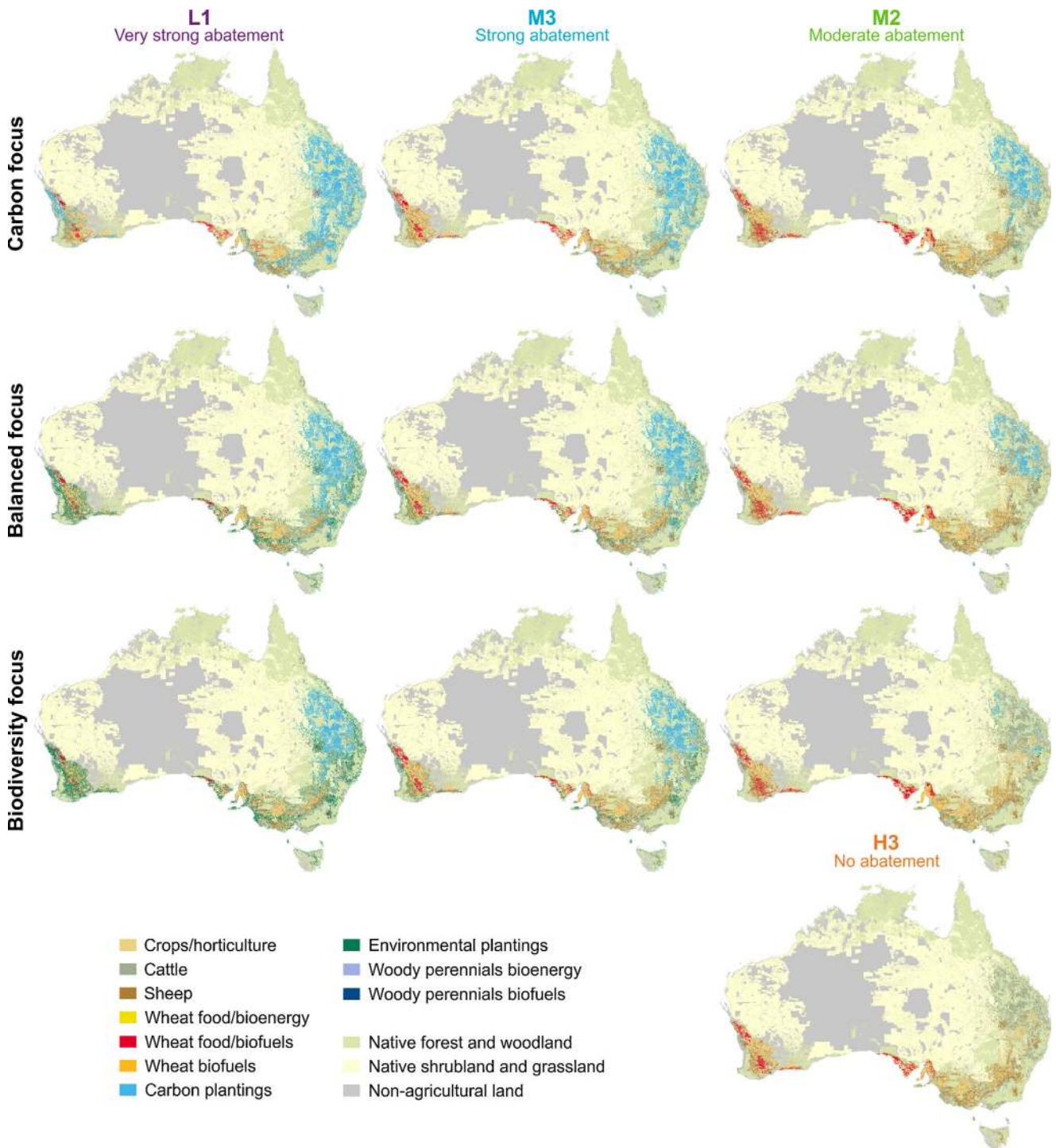

Fig. 6. Areas of land-use transition of broad agriculture types by 2050 under the four global outlooks and three domestic land-use policies (Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained).
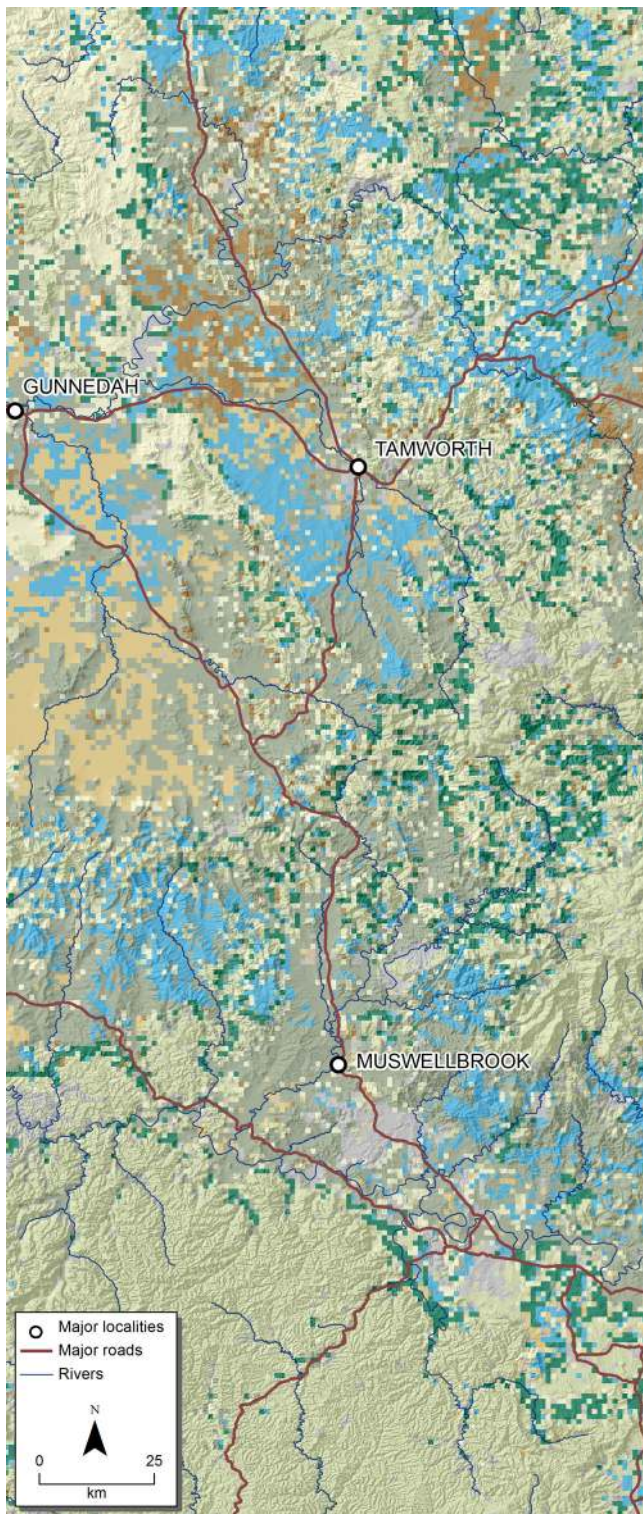
Fig. 7. Potential 2050 land-use under the four global outlooks and three domestic land-use policies (Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained). Note that limited variation occurred across domestic land-use policy foci under H3.
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plantings underway by 2020, and to environmental plantings by 2025 (Fig. 5). Under M2 Balanced focus, the potential area of land-use conversion was much less than M3 (18.4 Mha). Carbon plantings were still the dominant new land-use (10.3 Mha), with more biofuels cropping but little environmental plantings (1.5 Mha). Biofuels transition occurred throughout the time horizon, but large-scale carbon plantings only began around 2045 (Fig. 5). In H3, negligible reforestation occurred across all

three land-use policies, but there was some potential (5.4 Mha) for transition to biofuels cropping by 2050.

Carbon-focused domestic land-use policy resulted in slightly more potential for agricultural land-use transition (e.g. 40.0 Mha in M3) but the main influence of this policy strategy was to replace most environmental plantings occurring in the Balanced focus land-use policy with carbon plantings. Land-use transition to carbon plantings also occurred about 5 years earlier. A biodiversity

Fig. 8. Illustration of the high spatial resolution of land-use modelling showing potential 2050 land-use under the M3 global outlook for central New South Wales (Fig. 1) (Balanced focus, Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained). The legend is shown in Fig. 7.

focus slightly reduced the potential for agricultural land-use change and increased the potential for environmental plantings (11.1 Mha, 13.7%), replacing carbon plantings. Land-use transition tended to occur about 5 years later under the Biodiversity focus compared to the Balanced focus (Fig. 5, S1 Video–S12 Video).

Adoption behaviour, productivity growth, and capacity constraints had a significant influence on land-use change (S1 Fig–S54 Fig). Increasing the adoption hurdle rate reduced and delayed potential land-use change. For example, under M3 Balanced focus with medium productivity, the potential area of land-use transition decreased with increasing hurdle rate, ranging from 51.7 Mha to 23.5 Mha under the 1 × and 5 × adoption hurdle rates, respectively. Productivity growth had a similar magnitude of effect, with land-use change increasing via the enhanced productivity and profitability of new reforestation and energy crops, and price reductions of agricultural commodities resulting from increased supply. For example, under M3 Balanced focus with a 2 × adoption hurdle rate, the potential area of transition ranged from 25.2 Mha to 48.9 Mha under Low and High productivity growth, respectively. Combined high productivity growth and low adoption hurdle rate settings strongly increased the area of biofuels cropping, particularly under the M2 and H3 outlooks (S7 Fig).

Less land-use change occurred in the presence of capacity constraints, particularly in the L1 and M3 outlooks (S1 Fig–S54 Fig). For example, in M3 Balanced focus with capacity constraints, the potential for land-use change was 14.4 Mha (S14 Fig). Transitions to carbon plantings and environmental plantings in particular were reduced by the reforestation constraint. Similarly, early rates of transition to biofuels cropping were also reduced by limits to biofuel processing capacity and resulting feedstock demand. Potential land-use change accelerated over time following the constraint settings, with rapid change occurring by 2050.

3.2. Economic returns to land

Economic returns to land increased strongly in real terms over the period 2013–2050 under the L1 and M3 outlooks in response to the higher carbon prices and the potential for widespread transition to reforestation (Fig. 10). For example, by 2050 under M3 Balanced focus, economic returns increased to 58 $B yr^{-1} (+112%) from 2013, with most of this occurring after 2030. Under L1 Balanced focus, economic returns increased to 80 $B yr^{-1} (+192%) from 2013 to 2050 with increases beginning around 2020 and reforestation accounting for much of the additional increase. Returns to food/fibre production also increased due to greater global demand for crops and livestock (Fig. 3) and price responses to competition for land reducing food/fibre supply. Returns to land stagnated under H3, and decreased to 19 $B yr^{-1} (−31.7%) by 2050 under M2 Balanced focus due to the weak carbon price and lack of competition for land influencing supply-driven price increases, lower global demand for crops and livestock, and increasing costs of production (Fig. 3).

Most non-food/fibre returns came from carbon plantings under the Carbon focus, changing to environmental plantings under the Biodiversity focus (Fig. 10). Besides this switch, land-use policy did not have a strong effect on total economic returns to land.

Productivity growth had a complex influence on economic returns to land (S55 Fig–S72 Fig). Total economic returns decreased with increasing productivity growth rates. In M3 Balanced focus, returns ranged from 157 $B yr^{-1} to 98 $B yr^{-1} under Low and High productivity growth, respectively. At higher productivity growth, food/fibre returns decreased while returns to new non-food/fibre land-uses increased. This was due to the increasing profitability and competitive advantage of new non-food/fibre land-uses, with consequent supply-driven price reductions overwhelming the effect of increased productivity on agricultural profits. Economic returns to land also decreased with increasing adoption hurdle rate ranging from 123 $B yr^{-1} to 93 $B yr^{-1} under the 1 × and 5 × adoption hurdle rates, respectively. Capacity constraints also reduced returns to land with constrained M3 Balanced focus food/fibre production. These results illustrate the inefficiencies
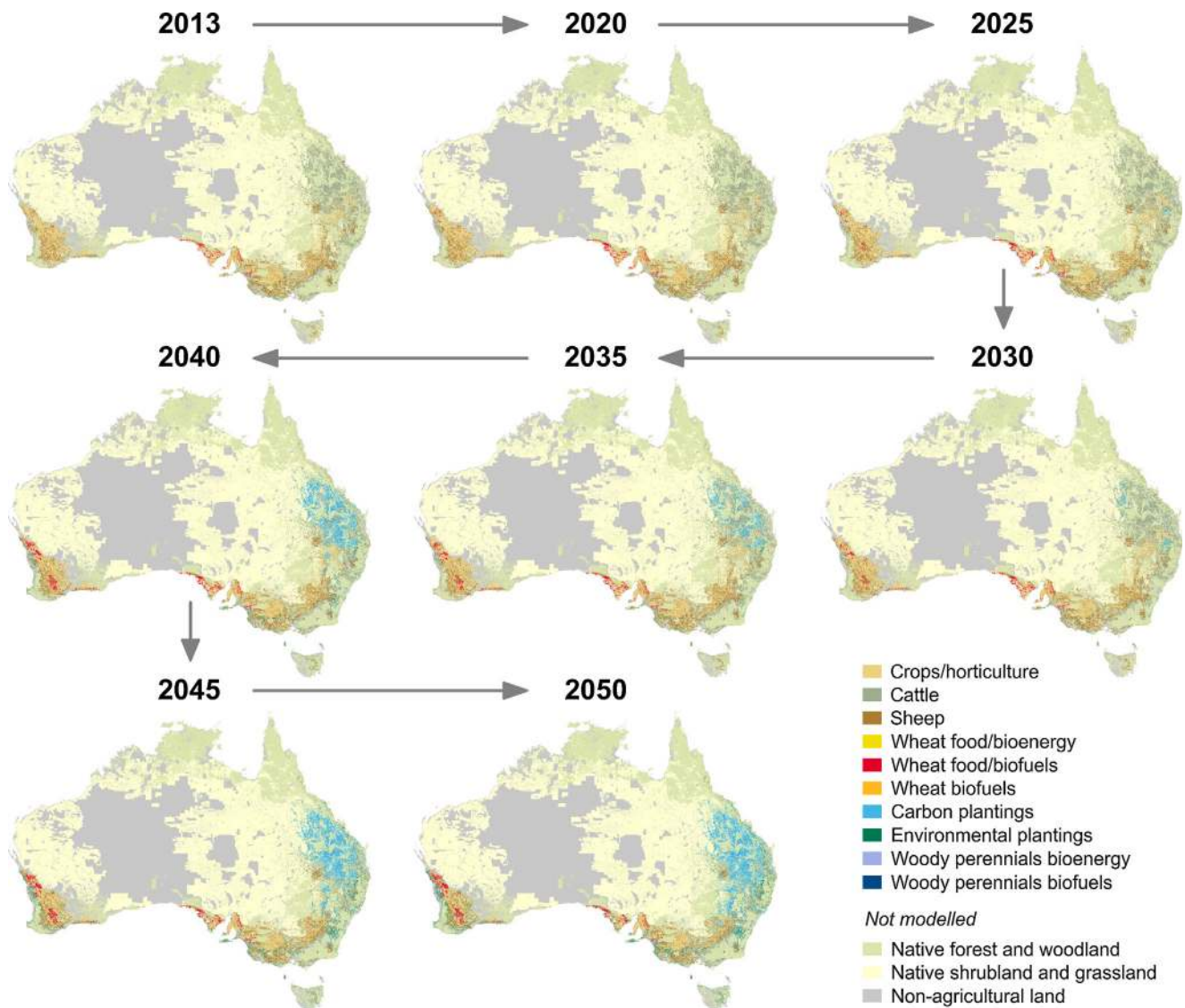
Fig. 9. Potential evolution of land-use from 2013 to 2050 under M3 (Balanced focus, Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained).

associated both with inertia in accruing 75\$B yr^{-1} by 2050, with increases occurring later and a greater proportion of returns from adoption of new land-uses by landholders, and in capacity constraints to land-use change.

3.3. Food and fibre production

Food/fibre production increased from 2013 to 2050 under most land-use scenarios and was strongly influenced by global outlooks, being highest under H3, then M2, M3, and lowest under L1 (Fig. 11). Over time, food/fibre production often displayed a peak-decline trend. For example, cattle production in M3 Balanced focus increased until 2025 due to increasing productivity, then plateaued until 2035 and declined to 2050 in response to competition for land. The focus of domestic land-use policy did not systematically affect food/fibre production. Crops/horticulture production increased from 2013 to 2050 under all combinations of global outlook and land-use policy, rising for example to 130.1 Mt (+59.9%) under M3 Balanced focus. Livestock production also increased under M2 (+53.8% cattle, +58.6% sheep) and M3 (+27.4%

cattle, +18.4% sheep), with cattle increasing slightly (+4.7%) and sheep decreasing (−11.8%) in L1.

Food/fibre production was sensitive to productivity growth, adoption hurdle rate, and capacity constraint assumptions (S73 Fig–S90 Fig). Higher productivity growth drove higher production, ranging from 89.5 Mt yr^{-1}, 15.5 million head yr^{-1}, and 49.2 million head yr^{-1} for crops/horticulture, cattle, and sheep production, respectively under Low productivity growth, to 162.7 Mt yr^{-1}, 24.2 million head yr^{-1}, and 71.2 million head yr^{-1}, respectively under High productivity growth, for M3 Balanced focus in 2050. Lower adoption hurdle rates led to a significant decline in food/fibre production, especially under L1 and M3, as landholders more readily changed land-use. For example, under M3 Balanced focus production in 2050 ranged from 126.0 Mt yr^{-1}, 18.2 million head yr^{-1}, and 50.0 million head yr^{-1} for crops/horticulture, cattle, and sheep, respectively under 1 × adoption hurdle rate, to 132.3 Mt yr^{-1}, 23.9 million head yr^{-1}, and 82.2 million head yr^{-1}, respectively under 5 ×. Capacity constraints led to increased food/fibre production (139.7 Mt yr^{-1}, 25.5 million head yr^{-1}, and 79.2 million head yr^{-1} for crops/horticulture, cattle, and sheep production, respectively) following less land-use transition.
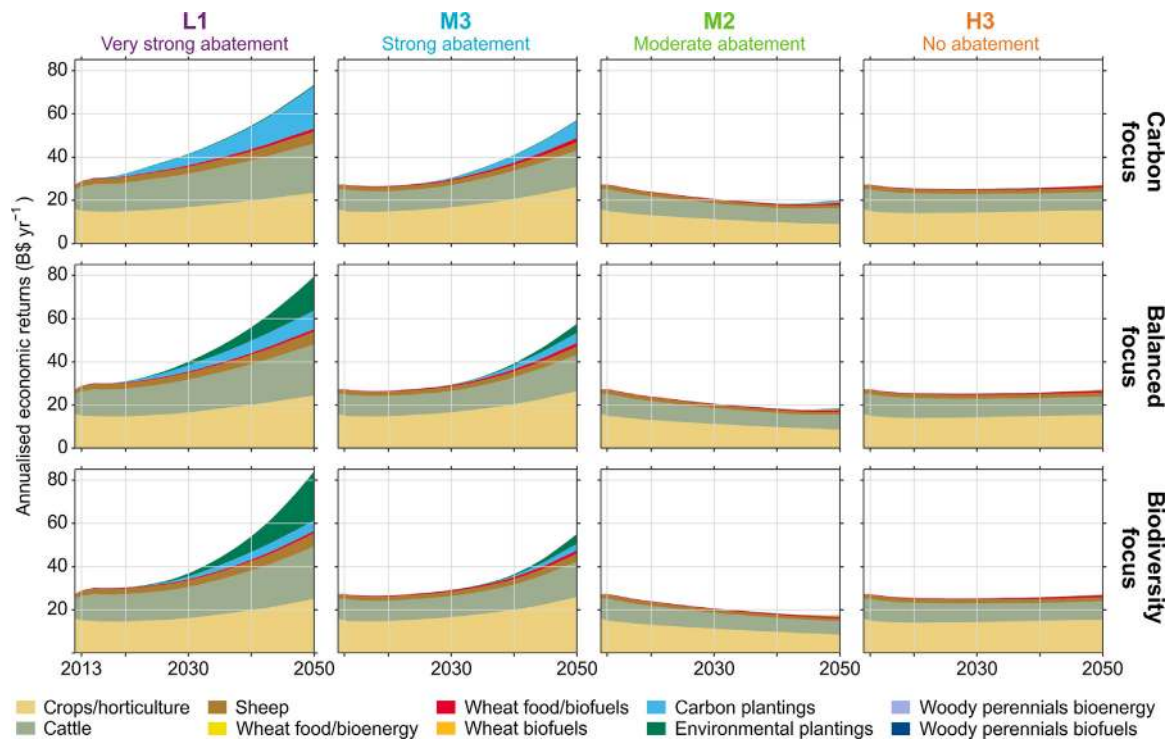
Fig. 10. Change in economic returns to land over time from 2013 to 2050 under the four global outlooks and three domestic land-use policies (Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained).

3.4. Emissions abatement

Substantial emissions abatement potential emerged by 2050, depending on both the global outlook and domestic land-use policy (Fig. 11). Annual emissions abatement in 2050 was similar under the L1 (554 $MtCO_2$ yr^{-1}) and M3 (519 $MtCO_2$ yr^{-1}) outlooks but L1 emissions abatement occurred earlier and plateaued after 2040 (Fig. 11). Cumulative emissions abatement to 2050 was greatest under L1 (11,592 $MtCO_2$), followed by M3 (5333 $MtCO_2$) and M2 (676 $MtCO_2$), and was negligible under H3. Large-scale abatement began around 2020 under L1, compared to 2030 for M3, and 2045 for M2 under the Balanced focus. Domestic land-use policy also influenced the amount and timing of abatement. For instance, for the M3 outlook, Carbon focus cumulative 2050 abatement totalled 7435 $MtCO_2$ and began around 2025, compared with 3207 $MtCO_2$ beginning around 2035 for the Biodiversity focus (Fig. 11).

Emissions abatement also increased with productivity growth (S73 Fig–S90 Fig). For example, for M3 Balanced focus, cumulative 2050 abatement ranged from 2497 $MtCO_2$ at Low productivity to 8569 $MtCO_2$ at High productivity. Adoption hurdle rate assumptions similarly influenced cumulative 2050 abatement which ranged from 7292 $MtCO_2$ at 1 × adoption hurdle rate to 2823 $MtCO_2$ at 5 × for M3 Balanced focus. Capacity constraints dramatically reduced emissions abatement (1638 $MtCO_2$) but did not substantively alter the timing (S73 Fig–S90 Fig).

3.5. Water resource use

Land-use scenarios had a significant impact on water resources largely due to increased interception following widespread reforestation (Fig. 11). Water resource use depended predominantly on global outlook and, to a lesser extent, domestic land-use

policy. Greatest water resource use occurred under L1 (29,785 GL yr^{-1} Balanced focus), M3 (20,924 GL yr^{-1}), and M2 (6,392GL yr^{-1}), with negligible use in H3. Global outlooks also influenced the timing of water resource impacts. For example, under M3 Balanced focus, significant impacts were felt by 2020 under L1, by 2030 under M3, and by 2045 under M2, following the onset of reforestation. Domestic land-use policy did not strongly affect water resources by 2050 but did affect the timing such that the stronger the Biodiversity focus, the later the impacts (Fig. 11). For example, water impacts were typically delayed by some 5 years for the Balanced focus compared to Carbon focus, and again for the Biodiversity focus compared to the Balanced focus. Increasing adoption hurdle rate and decreasing productivity growth reduced water resource use (S73 Fig–S90 Fig). For example, for M3 Balanced focus, 2050 water use ranged from 13,805 GL yr^{-1} to 25,982 GL yr^{-1} under low and high productivity growth, respectively, and from 26,011 GL yr^{-1} to 14,114 GL yr^{-1} under the 1 × and 5 × hurdle rates, respectively. Less water resource use occurred with capacity constraints imposed (e.g. 8387 GL yr^{-1} by 2050, M3 Balanced focus) (S73 Fig–S90 Fig).

3.6. Biodiversity services

Substantial differences in biodiversity services were found under global outlooks, with the greatest supply by 2050 occurring under L1 (56.4% Balanced focus) and M3 (37.4%) (Fig. 11). Biodiversity services increased rapidly after 2020 in L1, and after 2035 in M3. Under the Carbon focus in L1 and M3, and under all three domestic land-use policies in M2 and H3, biodiversity services were below 10.2% by 2050. Also evident in L1 were the greater biodiversity services supplied under the Biodiversity focus (67.3%) compared to the Balanced focus. Biodiversity services increased with higher productivity growth and decreased with
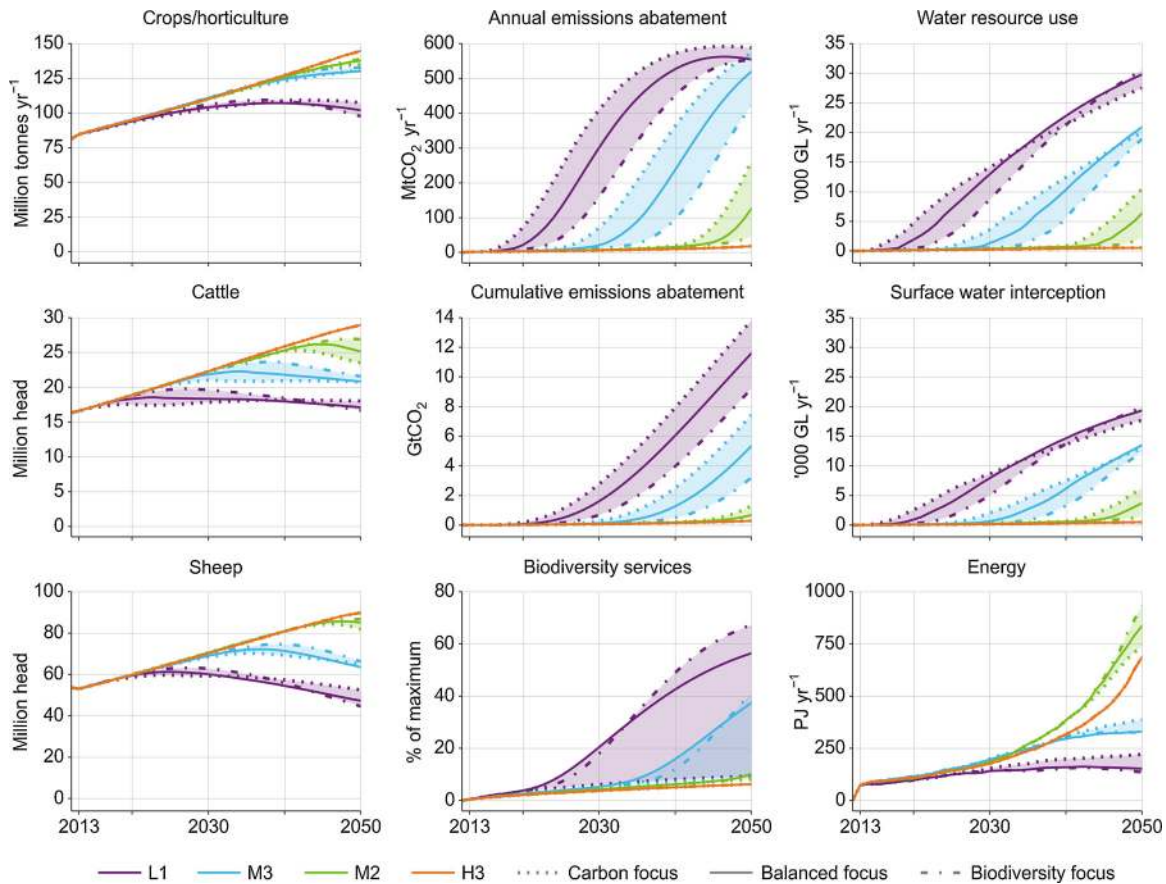
Fig. 11. Evolution of ecosystem services supply over time from 2013 to 2050 under the four global outlooks and three domestic land-use policies (Medium productivity growth, 2 × adoption hurdle rate, MPI-ESM-LR, unconstrained).

high adoption hurdle rate (S73 Fig–S90 Fig). For example, for M3 Balanced focus, biodiversity services ranged from 25.0% at Low productivity to 44.9% at High productivity, and from 46.7% at 1 × adoption hurdle rate to 22.5% at 5 ×. Capacity constraints decreased the supply of biodiversity services (e.g. 21.8% by 2050, M3 Balanced focus).

3.7. Energy

Energy production also varied significantly (Fig. 11) especially between global outlooks. With the Balanced focus, by 2050 the greatest energy production (836 PJ yr^{-1}) occurred under M2, followed by H3 (687 PJ yr^{-1}), M3 (330 PJ yr^{-1}), and L1 (152 PJ yr^{-1}). The majority (e.g. 89.5% for M2) of the energy produced was from wheat residue harvested to produce biofuels via lignocellulosic processing, with wheat grain sold into the food market. Biofuels were competitive under M2, and to a lesser extent H3 because of the smaller increases in crop and livestock demand, and low carbon prices, which reduced the competitiveness of agriculture and reforestation. Energy production increased steadily up to around 2030 in the M2 and H3 outlooks, then accelerated to 2050. Conversely, in the L1 and M3 outlooks, energy production tapered off after 2040 in response to competition for land from reforestation. While domestic land-use policy did not have a consistent effect (Fig. 11), higher rates of productivity growth strongly increased energy production (S73 Fig–S90 Fig). For example, in M2 Balanced focus, energy production ranged between 126 PJ yr^{-1} and 3857 PJ yr^{-1} under Low and High productivity growth. Adoption hurdle rate also had an influence with greater

energy production occurring under low hurdle rates such that at medium productivity, energy production ranged from 310 PJ yr^{-1} to 1317 PJ yr^{-1} under a 5 × and 1 × hurdle rate, respectively. Imposing capacity constraints severely reduced energy production, especially early on, and under the higher productivity growth-lower hurdle rate combinations. For example, with M3 Balanced focus, only 300 PJ yr^{-1} of energy was produced in 2050 under capacity constraints (S73 Fig–S90 Fig).

3.8. Integrated view of multiple ecosystem services

Taking an integrated view of the supply of multiple ecosystem services across all scenarios, several trends were evident (Fig. 12). With stronger emissions abatement action (i.e. L1, M3), greater emissions abatement was achieved but with higher water resource use, less food/fibre, and less energy. When combined with a Balanced or Biodiversity focus in domestic land-use policy, biodiversity services were also achieved. Supply of these ecosystem services were amplified when high productivity growth coincided with low adoption hurdle rates.

With weaker emissions abatement action (i.e. M2, H3), greater food/fibre and energy production was achieved and little water resource use occurred, but also with minimal emissions abatement and biodiversity services. Higher productivity growth increased both food/fibre and energy whereas higher adoption hurdle rate caused a switching from energy to food/fibre production. Capacity constraints had varied impact, ranging from a negligible effect in scenarios with little potential for land-use change, to a profound effect in strong change scenarios (S91 Fig).
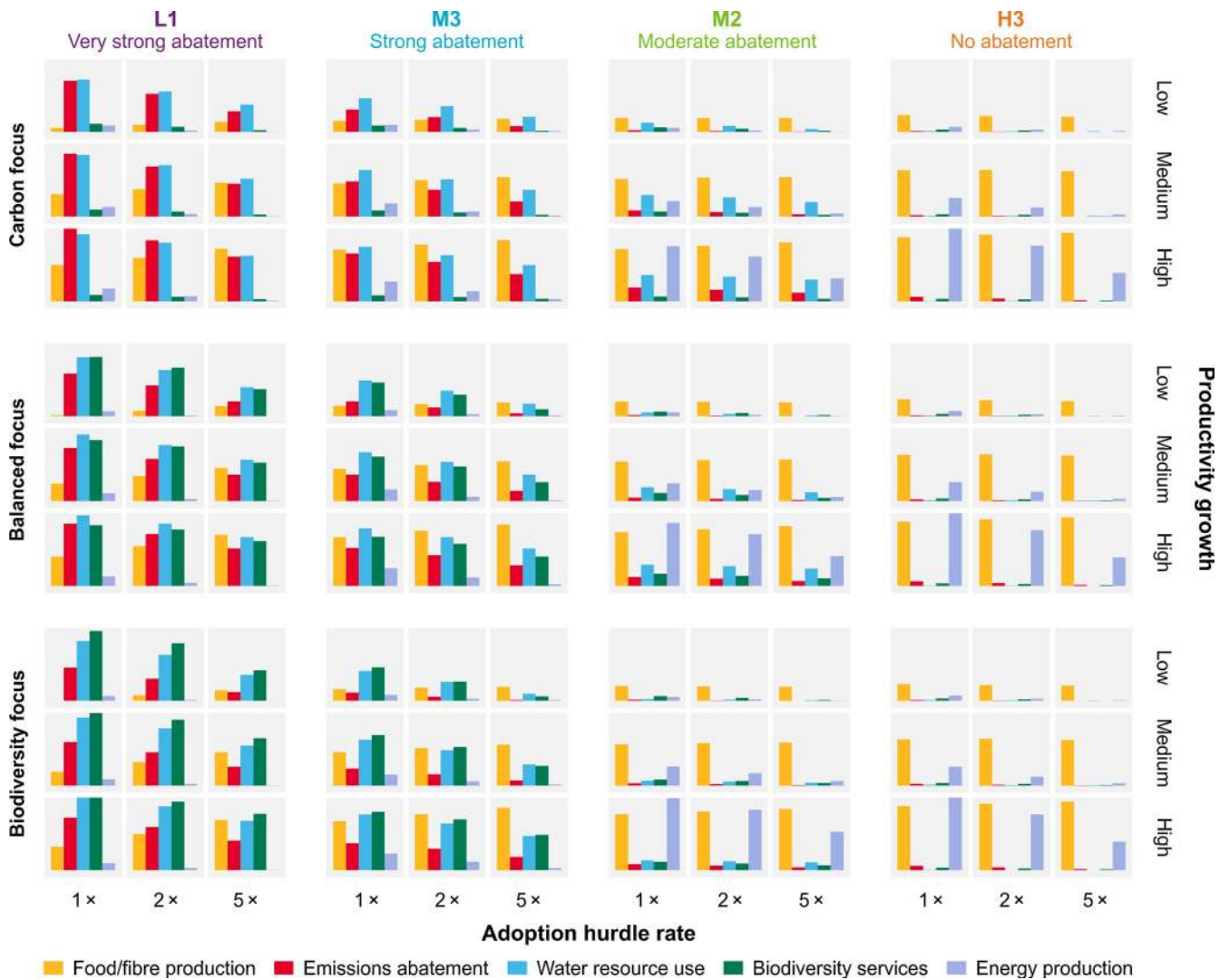
Fig. 12. Relative supply of ecosystem services at 2050 under the four global outlooks, three domestic land-use policies, three productivity growth rates, and three adoption hurdle rates (MPI-ESM-LR, unconstrained). Food/fibre production ranges from 30.2 $B yr^{-1} to 82.6 $B yr^{-1}, emissions abatement (cumulative to 2050) from 92.8 Mt CO_2 to 20,026 Mt CO_2, increase in water resource use from 214 GL yr^{-1} to 38,651 GL yr^{-1}, biodiversity services from 4.6% to 73.8%, and energy production from 16.3 PJ yr^{-1} to 5402 PJ yr^{-1}.

4. Discussion

We have quantified potential long-run future scenarios for Australian land-use and the impacts on economic and environmental sustainability indicators in response to interacting global environmental and economic change and domestic policy measures at high spatial and temporal resolution. The innovative analytic approach developed here has provided the most comprehensive and detailed continental-scale quantitative scenario analysis of land-use and sustainability yet. We found that strong potential future land-use and sustainability responses were possible. However, the exact nature of these responses and their magnitude, in addition to where and when they might occur, was sensitive to global outlook and the strength of the global emissions abatement effort, domestic land-use policy, and key uncertainty dimensions including land-use change adoption behaviour, productivity growth assumptions, and capacity constraints. The results have wide-ranging and specific implications for land-use and sustainability policy at global and domestic scales, and the methods developed here could be of great use to nations seeking to

balance development and mitigation strategies under future uncertainty.

4.1. Future land-use change and sustainability—a synthesis

While Gao et al. (2016) provides a detailed examination of the influence of input parameters on model outputs, a broader synthesis is provided here. Global outlooks strongly influenced land-use and sustainability. Although outlooks incorporated multiple different variables (i.e. climate, prices for carbon, oil, and electricity, and demand for crops and livestock), by far the strongest influence was carbon price (Connor et al., 2015; Gao et al., 2016). With stronger abatement incentives (i.e. L1, M3), reforestation outcompeted other land-uses over large parts of the study area, particularly in the beef grazing areas of southern Queensland and northern New South Wales. Weaker carbon incentives resulted in less land-use change, occurring later. With no carbon incentives in H3, energy prices drove change to food/biofuels cropping. The complementary domestic land-use payments were effective in converting more than half of the monoculture carbon plantings

under the Carbon focus, to environmental plantings under the Biodiversity focus. Higher adoption hurdle rates reduced the magnitude and delayed the timing of land-use change. Higher productivity growth rates had the opposite effect—via increasing the supply of agricultural commodities, agricultural prices, profitability, and competitiveness decreased. Capacity constraints also reduced rates of land-use change.

The location and timing of land-use change reflect threshold effects found previously in integrated environmental/economic assessments of land-use (Bryan et al., 2014b; Paterson and Bryan, 2012; Polglase et al., 2013). This effect occurs when specific economic, policy, and environmental conditions combine to render a new land-use highly competitive over a large, fairly homogeneous areas of agricultural land-use. For example, a dominant effect occurred in the economically marginal beef grazing area of southern Queensland which can also support fairly high rates of carbon sequestration (Evans et al., 2015). When the profitability of carbon plantings exceeded beef grazing, it tended to do so over the whole area which had similar land-use and economic profiles within a fairly narrow combination of parameter settings. Depending on the scenario settings (i.e. global outlook, domestic land-use policy, productivity growth, adoption hurdle rate etc.) and the associated trajectories in key parameters such as the carbon price, the profitability threshold was met and land-use change ensued at different dates.

Stronger incentives for emissions abatement under L1 and M3 also translated into much higher total economic returns to land. While new land-uses account for a good proportion of this, agricultural returns also increased due to higher global crop and livestock demand, and agricultural commodity price rises in response to land-use competition and reduced supply. Under the weaker global action outlooks (i.e. M2, H3), returns to land were dominated by agriculture and either remained stable (M2) or declined (H3). Domestic land-use policy had little effect on economic returns though it did vary the source between carbon plantings and environmental plantings. Increasing productivity growth had a weak, negative effect on economic returns to land-use through the effect of increased supply on commodity price, as did increasing adoption hurdle rate due to the inefficiency of lagged behavioural response to price signals. Returns in 2050 were similar under both capacity constraint settings but, in the stronger global action scenarios, they increased much later when constrained.

In parallel with the influence on land-use, higher carbon prices led to much higher rates of emissions abatement and biodiversity services, with reduced agricultural and energy production and greater water resource use. Conversely, under H3 with no carbon price, the highest levels of agricultural and energy production were achieved, with very little emissions abatement, biodiversity services, and water resource use. While it had little effect under weaker global action outlooks, domestic land-use policy focus was effectively able to substitute carbon sequestration for biodiversity, and *vice versa*, with little change in water resource use, or agricultural or energy production with stronger global action on emissions abatement. Higher adoption hurdle rates led to greater agricultural production and less emissions abatement, biodiversity services, water resource use, and energy production as land-use change occurred less and later. Higher productivity growth led to increased agricultural and energy production, emissions abatement, water resource use, and biodiversity services. This was due both to the increased productivity of agriculture and carbon plantings, and the reduced competitiveness of agriculture resulting from supply increases. Capacity constraints led to increased agricultural production and decreased and delayed emissions abatement, water use, and energy production.

4.2. Comparing results with previous work

While comparing our results against previous work is difficult for agriculture and water due to a lack of previous national-scale analyses, comparable assessments do exist for carbon sequestration, biodiversity, and energy. Our finding of strong potential for land-use change and land-sector supply of carbon sequestration is consistent with Garnaut (2008), CSIRO (2009), and Polglase et al. (2013), even with the latter two considering far lower carbon prices. Several other small-scale studies have also found substantial economic potential for carbon sequestration in specific parts of Australia (Evans et al., 2015; Flugge and Abadi, 2006; Flugge and Schilizzi, 2005; Harper et al., 2007; Hunt, 2008; Longmire et al., 2015; Maraseni and Cockfield, 2011; Paterson and Bryan, 2012; Paul et al., 2013a,b). However, key work (Burns et al., 2011) supporting Australian Government carbon price modelling found very much less potential. Differences were driven primarily by assumptions around the rates of potential land-use change as determined by the choice of a range of sensitive economic and behavioural parameters, and carbon sequestration rates. Biodiversity co-benefits generated by domestic land-use payments in this study are also consistent with previous national-scale (Bryan et al., 2014b; Carwardine et al., 2015) and regional (Bryan and Crossman, 2013; Crossman et al., 2011; Evans et al., 2015) findings. Our results are typically more conservative than previous efforts and our methods are potentially more robust, particularly owing to the use of internally-consistent, integrated-assessment-modelled global outlooks, the assessment of land-use competition, and the high-dimensional consideration of uncertainty. Our findings of substantial potential for biofuels were also consistent with previous studies (Bryan et al., 2010a; Farine et al., 2012). Wheat (grain and residue) as an energy crop could produce around one-third of projected Australian transport fuel use in 2050 (Graham and Smart, 2011) under M2 and H3, and potentially much more with high productivity growth and low adoption hurdle rates.

4.3. Implications for policy and governance

One of the greatest potential impacts of this work is in informing a national conversation about future directions for Australian land-use and sustainability. The results have already informed other analyses to provide a whole-of-economy picture of sustainability (Hatfield-Dodds et al., in review; Hatfield-Dodds et al., 2015b,c). However, there are also other wide-ranging and specific policy and governance implications for land-use; agriculture, productivity, and food security; regional development and structural adjustment; climate policy and emissions abatement; water resources; biodiversity conservation; and energy security.

Hotspots of land-use change occurred where and when specific land-uses tended to become competitive under certain scenarios. Understanding this potential can inform a range of targeted land-use policies designed to encourage positive change, or to discourage undesirable change. Mechanisms could range from local government planning regulations, through to targeted catchment-, regional-, or national-scale incentive schemes.

Economic returns to land increased with stronger global emissions abatement action. Australian farmers have long struggled with declining terms of trade and burgeoning debt to the point where agriculture is a marginal enterprise in many regions. The injection of new income streams, particularly from carbon and biodiversity payments, could provide transformational economic opportunities for Australia's regions, reversing long-terms declines, boosting regional development, revitalising rural communities, diversifying farm income sources, improving sustainability, and reducing reliance on other subsidies (e.g. exceptional circumstances payments).

Projections indicate that although significant reductions in the area of agricultural land-use were possible, agricultural production nevertheless tended to increase due to productivity improvements and the conversion of the least productive land (Grundy et al., 2016). Our results show that continued Australian contributions to global food security through agricultural exports depends on sustained productivity growth supported by investment in agricultural research and development, and production being concentrated in the best farming areas. Structural adjustment and incentive payments could be targeted at helping those areas of comparative advantage transition to ecosystem service provision (i.e. carbon sequestration, biodiversity, energy) instead of agricultural commodities.

Under very strong global emissions abatement action, land-sector abatement potential, particularly carbon sequestration, could exceed Australia's total current greenhouse gas emissions by 2040. In this scenario, abatement would begin after 2020, with most abatement coming online after 2030. Thus, the land-sector has potential for contributing to emissions abatement targets. Weaker global action however, reduced and delayed abatement. To achieve land-sector abatement, payment scheme design will need to account for high upfront costs, long project life, and long payoff periods. In general, landholders will require stronger financial incentives where they bear more policy-related risks (e.g. market price), but are likely to accept lower payments where these risks are shared or borne by others (e.g. through insurance or long-term contracts). In addition, the ability of forest stands to store carbon is finite—as carbon sequestration rates rise initially, peak, then decline to near zero in mature stands. This indicates that reforestation emissions abatement will be temporary (Pacala and Socolow, 2004), buying time for long-term, low-carbon structural changes in the energy sector and broader economy.

Water resource use increased most significantly under extensive reforestation scenarios, illustrating the potential scale of surface and groundwater impacts. Water resource impacts are unintended consequences from a failure of governance arrangements to account for multiple interactions and trade-offs (Bryan, 2013; Bryan and Crossman, 2013; Bryan et al., 2015a; Hejazi et al., 2014). The upfront costs of water entitlements incurred by reforestation in this study did not adequately reflect the scarcity value of water. Stronger water governance is needed which brings all users under a cap on resource use and requires reforestation to compete for water with other users (i.e. irrigators, urban, industrial) via market trade (Connor et al., in review).

Substantial biodiversity co-benefit opportunities were created by domestic land-use policy shifting the focus of abatement incentives more towards biodiversity (Bryan et al., 2014b; Bryan et al., 2016). In isolation, the base payment budget of $125 M achieved limited co-benefits. The levy on carbon plantings both reduced the competitiveness of carbon plantings relative to environmental plantings and dramatically increased the budget for targeting cost-effective payments for biodiversity services. However, recent work suggests that the use of an integrated carbon-biodiversity benefits metric for targeting biodiversity payments may be more efficient than a levy (Bryan et al., 2016).

Energy production from Australian agricultural land could be significant under specific future environmental and policy conditions. Establishing a biofuels industry would require a strong co-development policy as has been implemented in the USA and Europe. Biofuels was dependent on weak global emissions abatement action since this limited the competitiveness of reforestation. Effective policy to increase biofuels production in Australia will need to address competition for land. Bioenergy was not viable over large areas under any scenario, contrasting with previous findings which did not consider competition for land (Bryan et al., 2010b, 2008).

Timing of land-use change and ecosystem service supply is crucial, particularly for emissions abatement and biodiversity services. To avoid the worst impacts of climate change, it is generally accepted that stronger action is required sooner (Stern, 2006). Equally, for biodiversity conservation, restoration and reconnection of fragmented ecosystems is required urgently to reverse extinction processes (Kuussaari et al., 2009). Policy choices need to be informed not only by the magnitude of their impact on land-use change and ecosystem service supply, but also by the timing in the context of the urgency of the issue. Global outlooks and domestic land-use policy focus both strongly influenced the timing of land-use change and the impacts for ecosystem services. Increased adoption hurdle rate reduced the amount of land change and delayed it by up to a decade. Capacity constraints had a similar effect. Both the lagged response and capacity constraints also limited policy efficiency by reducing total economic returns to land. To achieve prompt, efficient, and desirable change, policy mechanisms such as information, extension, and awareness programs are required to reduce the behavioural inertia commonly found in land-use change decisions (Regan et al., 2015). Confidence in long-term institutional settings (e.g. via long-term contractual arrangements) is also central to achieving policy objectives that require long-term private investments, reducing risk, and increasing adoption rates. Government partnerships with the private sector in large scale reforestation capacity and the establishment of processing facilities may be needed to reduce capacity constraints on land-use change and increase policy efficiency (Yang et al., 2010).

4.4. Innovation, contribution, and generality

We have described a bottom-up, comprehensive, integrated, continental-scale land systems scenario analysis of potential future land-use responses and the impacts for economic and environmental sustainability which makes several significant land science advances. Building on previous major contributions (Bateman et al., 2013; Lawler et al., 2014; Schroter et al., 2005), we assessed: multiple potential land-use options and land-use competition; multiple indicators of environmental and economic sustainability; and intersecting global change and domestic policy responses under uncertainty for a globally significant region. With our annual time step and ~1.1 km grid cells, we captured trends over time and space at much higher resolution than other comparable, continental or global scale models which typically operate at 5–10 year time steps and 10–50 km grid cell resolution (Alcamo et al., 2011; Havlik et al., 2011; Leclère et al., 2014; Schaldach et al., 2011). Hence, LUTO is uniquely able to capture important localised processes of economic and environmental sustainability (e.g. sub-farm profitability, catchment hydrology, ecological connectivity) (Bateman et al., 2013; Connor et al., 2015; Verburg et al., 2013). LUTO is also strongly linked to global dynamics in environmental, economic, and energy systems (Graham, 2013; Newth et al., 2015, 2013; Reedman and Graham, 2013). Our comprehensive synthesis of long-run land system sustainability provides a basis for informed national strategic decision-making in Australia, and the accompanying data set (Bryan et al., 2015b) provides a unique resource for further research.

We have built substantively upon an emerging tradition of major foresighting and scenario analyses for Australia which have addressed specific issues such as climate change (http://www.climatechangeinaustralia.gov.au/), society and the economy (Australian Treasury, 2015), population and the environment (Raupach et al., 2012), carbon emissions (ClimateWorks Australia et al., 2014), and resilience (Cork, 2010). In particular, we substantially extended the work of Garnaut (Garnaut, 2008, 2011) which provided a comprehensive and quantitative, but broad-scale assessment of future climate and abatement scenarios for Australia and identified both significant impacts of climate

change on the land sector, and significant potential for it to contribute to climate change mitigation. As part of the Australian National Outlook (Hatfield-Dodds et al., in review; Hatfield-Dodds et al., 2015b,c), this work also informs the broader sustainability of the Australian economy, environment, and society.

Future influence of climate, population, policy, market forces, technology, and affluence on land-use and sustainability will affect all nations in ways that are impossible to predict. Many nations could benefit from this kind of quantitative, integrated, policy-relevant scenario analysis as they strive for strategic policy and governance responses for managing potentially transformative change in land-use and sustainability (Alcamo et al., 2008; Bryan et al., 2013; Gerland et al., 2014; IPCC, 2013; Newell et al., 2014; Wise et al., 2009). Such scenario analyses could be tailored to address the emerging and interacting challenges of emissions abatement, climate change adaptation, and food, water and energy security. Given the availability of key data layers, the LUTO model itself is directly applicable to other regions with similar social-ecological contexts (e.g. Europe, the US). However, greater modification will be required for different the socio-ecological system (e.g. tropical subsistence agriculture, African smallholder cropping). In each case, major quantitative scenario analysis is not simply a *plug and play* exercise. Nuance in the influence of specific policy combinations and dependencies over space and time found for Australia demonstrates that a tailored approach is crucial to understanding land-use and sustainability trajectories in other regions (Bateman et al., 2013). Successful scenario analyses depend upon combining a deep understanding of the complex systems involved, co-development of scenarios and key uncertainties with stakeholders, and a strong connection to multiscale quantitative modelling (Alcamo and Henrichs, 2008).

4.5. Assumptions, limitations, and future directions

The results should be interpreted with full cognisance of the many assumptions and limitations of the methods used. The primary caveat is that the scenarios presented are modelled projections of possible futures arising from explicit combinations of model settings, and designed to inform strategic thinking and decision-making. They are not forecasts or predictions of the future and we make no judgment on the likelihood of specific scenario assumptions nor, of course, specific outcomes. We have treated uncertainty via scenario analysis across the most influential dimensions as revealed by global sensitivity analysis (Gao et al., 2016) of global outlook, domestic policy treatment, productivity growth, adoption behaviour, climate change, and capacity constraints. We specified low, medium, and high boundary conditions along most of these dimensions for scenario analysis. We acknowledge that the influence of these drivers will be influenced by the plausible range of uncertainty in each of these dimensions. We also recognize that there is residual uncertainty with each of the 648 scenarios. Using the typology of Warmink et al. (2010), this residual uncertainty is dominated by uncertainty in the technical specification of input model parameters related to natural variability. Uncertainty in other model input parameters (Table S1) can lead to uncertainty in the outputs for each scenario (Gao et al., 2016), but this is likely to be minor compared to the variation between scenarios.

A fundamental assumption is that the supply of Australian agricultural commodities reflects global supply and this underpins the partial equilibrium agricultural price response which provides a dampening effect and counters *runaway* land-use change. For example, price feedbacks reduced land-use change by around 6% in M3 and 21% in L1 (Connor et al., 2015). We did not consider competition between agricultural land-uses or intensification of land management, and assumed that no new higher-value

agricultural land-uses emerged. Largely based on generalised future trends in mean parameter values (e.g. rainfall and temperature, price and demand trajectories, productivity growth, adoption behaviour), the modelling did not consider variability over time—a key factor in land-use decision-making under uncertainty (Reeson et al., 2015; Regan et al., 2015). In particular, trajectories in the influential oil price parameter from the GIAM model were similar between outlooks due to price inelasticity, fail to capture price volatility such as that seen in 2008 and 2015. Also, trajectories for some time-invariant parameters could be estimated (e.g. water use by trees, and fire and drought risk) or improved (e.g. climate change impacts on crops and trees) with additional modelling and data. We did not assess effects on regional communities, nor fully explore the impacts on ecosystem services such as soil carbon, land degradation, sedimentation, water quality, and amenity and recreational values.

Although our model covers over 85% of the gross value of Australian agriculture; emerging land management, development, and sustainability issues in Northern Australia warrant its extension. Similarly, we initially excluded Australia's natural estate from the analysis as all jurisdictions had broadacre land clearance regulations in place. However, recent relaxation of state-based regulations means that deforestation is again a major land change issue in Australia (Bradshaw, 2012).

The potential impacts of intersecting global change and domestic policy on land-use and sustainability in Australia are clear—under specific combinations, land-use responses can increase and diversify economic returns to land and produce a range of ecosystem services such as emissions abatement, biodiversity services, and energy, without substantial impacts on agricultural production. However, better governance is required to manage water resource impacts. Although the scale and pace of the highest estimates of land-use change may seem difficult to imagine, several analogues exist, e.g. post WWII land clearance (Bradshaw, 2012) and the expansion of coal seam gas (Hobday and McDonald, 2014) in Australia, farmland abandonment and forest recovery in South America (Grau et al., 2004) and eastern Europe (Kuemmerle et al., 2011), and China's large scale reforestation programs (Liu et al., 2008). We do not attempt to account for societal constraints such as a *social licence* for large-scale land-use change, nor comment on its desirability. We make no inference about the likelihood of any particular scenario but we are confident that the results are robust to uncertainty given the scenario assumptions. We present this information to support public discussion about the merits of potential change, and the suite of policy options available to promote sustainable landscapes and communities in a dynamic and evolving world.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.03.002.

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