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

Brett A. Bryan[a,*], Martin Nolan[a], Lisa McKellar[b], Jeffery D. Connor[a], David Newth[c], Tom Harwood[d], Darran King[a], Javier Navarro[b], Yiyong Cai[c], Lei Gao[a], Mike Grundy[e], Paul Graham[f], Andreas Ernst[g], Simon Dunstall[g], Florian Stock[g], Thomas Brinsmead[f], Ian Harman[c], Nicola J. Grigg[d], Michael Battaglia[h], Brian Keating[i], Alex Wonhas[j], Steve Hatfield-Dodds[d]

[a] CSIRO Land and Water, Waite Campus, Urrbrae SA 5064, Australia
[b] CSIRO Land and Water, EcoSciences Precinct, Dutton Park, Qld 4102, Australia
[c] CSIRO Oceans and Atmosphere, Black Mountain, Canberra ACT 2601, Australia
[d] CSIRO Land and Water, Black Mountain, Canberra ACT 2601, Australia
[e] CSIRO Agriculture, EcoSciences Precinct, Dutton Park, Qld 4102, Australia
[f] CSIRO Energy, Newcastle, NSW 2300, Australia
[g] CSIRO Digital Productivity, Clayton, Vic 3168, Australia
[h] CSIRO Agriculture, Sandy Bay, Tas 7005, Australia
[i] CSIRO Executive, EcoSciences Precinct, Dutton Park, Qld 4102, Australia
[j] CSIRO Executive, North Ryde, NSW 2113, Australia

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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.

* Corresponding author.
E-mail address: brett.bryan@csiro.au (B.A. Bryan).

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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.,