



Simple models for managing complex social–ecological systems: The Landscape Futures Analysis Tool (LFAT)



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ABSTRACT

Integrated modelling and assessment can facilitate exploration of complex social–ecological interactions and quantify trade-offs in regional policy, planning, and management options. However, there have been challenges in its acceptance and adoption for supporting decisions. Here we overcome this *implementation gap* through the development of an interactive online tool called the Landscape Futures Analysis Tool (LFAT) (<http://www.lfat.org.au/>). Identifying four high priority regional management issues; agricultural production, carbon sequestration, biodiversity conservation and weed management, we developed a series of simple models to explore them through a range of environmental and economic scenarios including climate change, carbon price, agricultural commodity price, and production costs. These models were implemented within the LFAT to allow users to select, query and explore combinations of key variables and examine their impact on each of the management issues through a range of interactive maps and summary statistics.

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1. Introduction

Increasing global demand for food, energy, water, and other ecosystem goods and services, combined with the need to mitigate and adapt to climate change, is generating unprecedented competition for land (Bryan et al., 2013; Foley et al., 2011; Smith et al., 2010). Policy, planning, and management (hereafter simply *management*) of competing land uses and their impacts on natural capital and ecosystem services have been largely implemented at a landscape scale through regional management (Hajkowicz, 2009; Jones et al., 2013; Robins and Dovers, 2007). The complexity of environmental, economic, and social processes interacting over space and time in regional social–ecological systems (Liu et al., 2007) makes it difficult to tease out cause and effect, to identify

leverage points for targeting management interventions, and to judge the likely effectiveness of those interventions. Increasingly, there is a need to identify key system drivers and explore variation across multiple future scenarios for supporting decisions (e.g. Dale et al., 2013). With a large number of variables it can be particularly difficult to forecast the future influence of management strategies with much certainty (Prato, 2007). Further complicating matters, planning horizons are often short relative to the time frames of the social–ecological processes that respond to intervention. To make informed management choices, decision-makers need to understand the impacts of a range of available options on multiple natural capital assets and ecosystem services as well as social-economic outcomes under future scenarios (Bateman et al., 2013).

Integrated assessment and modelling (IAM) can provide valuable information that can quantify complex social–ecological processes and interactions, inform stakeholders, and help decision makers weigh-up the costs, benefits, and trade-offs of regional management options (Jakeman and Letcher, 2003; Laniak et al., 2013). IAM tools can be used to explore the influence of management in the context of multiple interacting economic and

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environmental drivers that motivate land use and management changes over time which, in turn, result in multiple benefits and trade-offs for natural capital and ecosystem services (Bryan, 2013). For example, exploring planning scenarios of various combinations of cropping, grazing, forestry, biofuel production, and residential development, Goldstein et al. (2012) integrated ecosystem services and economic outcomes to identify land use options that satisfied diverse stakeholders and planning objectives. Similarly, Raudsepp-Hearne et al. (2010) examined bundles of ecosystem services and identified trade-offs between provisioning services (e.g. agriculture and fresh water), cultural services (e.g. recreation and tourism) and regulating services (e.g. carbon sequestration and soil fertility). Examining the economic potential for land use change from traditional agriculture to carbon monocultures and environmental plantings, Bryan and Crossman (2013) found complex interactions between financial incentives and the provision of multiple ecosystem services (i.e. food and fibre, fresh water, carbon sequestration, habitat).

Despite the success of IAM in understanding future alternatives for regional social–ecological systems, the outputs have often not been widely adopted in regional policy, planning, and management. This problem has been recognized as the *implementation gap* in conservation planning where sophisticated plans have rarely been adopted in practice (Knight et al., 2008; Luz, 2000). Part of the problem is that typically short planning horizons have focussed on the more immediate issues in managing regional natural capital and ecosystem services rather than longer term future impacts. However, increasing realization and acceptance of the long term and complex nature of regional social–ecological processes and the need to manage them is promoting greater interest in the outputs of IAM. In response, several attempts have been made to make IAM outputs more accessible and encourage its use in supporting decision making for regional management. For example, companion modelling has been used within participatory frameworks to engage stakeholders in the design and development of land and water management plans (e.g. Etienne et al., 2011; Gurung et al., 2006). Other deliberative processes that seek to enhance stakeholder understanding, interaction and participation have also been used to improve management decisions in complex settings with competing interests (e.g. Bryan and Kandulu, 2011; Cundill and Rodela, 2012; Garmendia and Gamboa, 2012; Hewitt et al., 2014). Some recent studies have incorporated visualisation methods (e.g. Pettit et al., 2011) and web-based interfaces (e.g. Labiosa et al., 2013; Rao et al., 2007) to deliver complex, integrated landscape scale information and facilitate participatory planning for supporting regional decision making. Similarly, many products such GIS plugins (e.g. Pert et al., 2013; Sharp et al., 2014) or web-based interfaces (e.g. Liekens et al., 2013) have been developed through community-based engagement processes in order to tailor their product and promote implementation. Nonetheless, barriers to accessing and using complex information for supporting regional policy, planning, and management decisions still remain due to several factors including limited quantitative analytical capacity, limited time and willingness to engage with information, and the need for specialized technical requirements such as software or data.

In this paper we outline the development and parameterisation of a web-based tool designed to overcome the implementation gap. The Landscape Futures Analysis Tool (LFAT) was built around series of simple models presented within an online interface designed to facilitate the exploration of environmental and economic scenarios on landscape futures for supporting regional management decision making. Four high priority regional planning issues were identified through a process of community engagement. These issues; agricultural production, carbon sequestration, biodiversity

conservation, and weed management, were each addressed using different simple analytical models that were implemented within the online interface by way of separate planning modules. The online interface allows users to define a range of scenarios within each module in order to explore combinations of key variables and examine the impact on agricultural production, carbon sequestration, biodiversity conservation and weed management through visual outputs including interactive maps and summary statistics. By combining the simple models and the online interface the LFAT overcomes some of the barriers to using complex information for supporting regional policy, planning and management decisions. It provides excellent quantitative analytical capacity, a sound platform through which to engage with the information and overcomes limitations due to specialized technical requirements. In order to demonstrate LFAT functioning and outputs we provide a case study from the Eyre Peninsula Natural Resource Management (NRM) region including implementation and model parameterisation. The LFAT can be accessed directly through the website <http://lfat.org.au/lfat>.

2. Methods

The LFAT has been specifically designed so that different data can be used to parameterise each of the simple analytical models and thus facilitate easy application of the tool to different regions. This is reflected in the structure of the Methods below. In Section 2.1 (Engagement process) we briefly outline the engagement process through which the different planning issues were identified. In Section 2.2 (Model description) we explain the simple models that were developed to address each of the planning issues. In Section 2.3 (Online interface) we describe the spatial analysis tools that enable exploration of the models and the integration of the data within the online interface. In Section 3 (Model implementation and results) we provide a case study of the LFAT implementation and parameterisation with worked examples.

2.1. Engagement process

The simple models and the online delivery system that make up the LFAT were designed through an engagement process with regional planners and decision makers in the Murray–Darling Basin and the Eyre Peninsula regions in South Australia. Focus groups consisting of stakeholders from natural resource management groups, farming representatives and relevant government departments were established to review regional planning and policy development. Meetings were organised for each of the regions with between 15 and 20 people attending. A series of predetermined questions focussing on the process, information, data and scientific tools used for planning and policy development were used to guide the group discussions (Supplementary Material S1). This process is described in detail in Meyer et al. (in preparation). These discussions were analysed to identify key regional planning issues that suffered from knowledge gaps within the planning and policy development process as well as impediments to accessing the necessary information to overcome these gaps. The findings of this process identified agriculture, biodiversity, weeds and carbon farming as important landscape planning issues along with the need to explore how these issues were affected by commodity price and market fluctuations. This process also identified technological and software impediments to accessing this information in a format that was accessible and easy to interpret. Another prescient requirement to meet regulatory planning requirements, was the ability to explore the uncertainty associated with climate change. The LFAT was developed to meet these needs and provide access to this complex regional information in a simple and accessible

format. The engagement process continued after development of the tool to provide training for end users who had been involved in the development. Training consisted of working through various examples before providing assistance while users worked through their own planning issues. Informal feedback was provided by these end users throughout this process in order to help refine the utility and accessibility of the underpinning information and functionality of the interface.

2.2. Model description

The LFAT was built around four modules, each addressing a priority regional management issue, and each employing a simple, tailored analytical model. The Agricultural Production module used a systems modelling approach, the Carbon Sequestration module used spatial multi-criteria analysis, the Biodiversity Conservation module used cost-effectiveness analysis, and the Weed Management module used risk analysis. Users can interact with each of the modules through the online interface when using the LFAT by way of check boxes and threshold sliders. This allows users to select different options and thresholds in order to explore the impact of different price, cost and climate scenarios.

Within each of the four modules, the simple model was developed to explore the impact of environmental and economic scenarios relevant to the specific regional management issue. Scenarios captured variation in the key drivers of climate (denoted s in the set of scenarios S), agricultural commodity price (denoted p in the set of price multipliers P), production cost (denoted c in the set of cost multipliers C), and carbon price (denoted u in the set of carbon prices U). While the modules were designed to identify and analyse individual regional issues, there were significant connections between each module as the four issues are related in practice. For example, in identifying areas for ecological restoration the

$$\mathcal{G}_{s,p,c,u} = \begin{cases} 1 & \text{where } \prod_{v \in V^<} \mathbf{y}_{s,p,c,u,v} < y'_{v^<} \times \prod_{v \in V^>} \mathbf{y}_{s,p,c,u,v} > y'_{v^>} = 1 \\ 0 & \text{otherwise} \end{cases}$$

Equation 2

user has the opportunity to consider the agricultural productivity of land and the potential impact of different ecological weeds. Below we explain each module and the simple model underpinning it. While each of the variables that make up the models are explained in this section they are not parameterised here. An example of how these variables could be parameterised is described in Section 3 (Model implementation and results).

2.2.1. Agricultural production – systems modelling

The *Agricultural Production* module uses a systems modelling approach for exploring potential agricultural yields and economic returns under changing climate and economic conditions. Projections of agricultural yield under relevant climate scenarios are needed to populate this approach. A profit function is used to quantify the impact of changes in yield, agricultural commodity prices, and energy costs on the net economic returns from agriculture. Economic returns from agriculture (π^{AG} , bold notation denotes spatial layer throughout) are calculated as the product of yield \mathbf{q}_s adjusted for each climate change scenario s in the set of scenarios S , and commodity price \mathbf{p}^{AG} adjusted by the commodity price multiplier p in P , minus the costs of production \mathbf{c}^{AG} adjusted by the production cost multiplier c in C .

$$\pi_{s,p,c}^{AG} = \mathbf{q}_s \cdot p \cdot \mathbf{p}^{AG} - c \cdot \mathbf{c}^{AG}$$

Equation 1

2.2.2. Carbon sequestration – spatial multi-criteria analysis

The *Carbon Sequestration* module uses a spatial multi-criteria analysis (MCA) model to identify cleared areas most suitable for the reforestation of monoculture tree plantations for carbon sequestration (or *carbon plantings*). The MCA can create inclusion (*go*) and exclusion (*no go*) zones for carbon plantings under different climate, cost, and price scenarios based on user-defined thresholds across a suite of spatial criteria, all of which were identified in the participatory engagement process. Criteria include rates of carbon sequestration, agricultural production rates, the profitability of carbon plantings and agriculture, fire risk, soil erosion, dryland salinization, biodiversity, and water quantity and quality. The spatial multi-criteria analysis identifies areas where carbon plantings are permitted which satisfy all spatial criteria. Users can specify minimum ($v^>$) or maximum ($v^<$) thresholds for the spatial criteria. For example, carbon plantings may only be permitted outside of prime farm land (i.e. where yields are less than a maximum threshold), in areas close to waterways to improve water quality (i.e. distance to streams less than a maximum threshold), in areas of low biodiversity value (i.e. priority score less than a maximum threshold), or in areas far from urban centres to reduce fire risk (i.e. distance from towns greater than a minimum threshold). We framed each threshold y'_v for criteria v in the sets of minimum $V^>$ and maximum criteria $V^<$ to identify where carbon plantings are permitted. The model calculates a layer \mathcal{G} which identifies the *go/no go* areas for carbon plantings where each spatial criteria layer $\mathbf{y}_{s,p,c,u,v}$ meets the relevant threshold across all criteria under each climate scenario s , commodity price multiplier p , production cost multiplier c , and carbon price u where relevant:

2.2.3. Biodiversity conservation – cost-effectiveness analysis

The *Biodiversity Conservation* module uses a cost-effectiveness approach to identify the most cost-effective areas for the conservation of remnant habitat and the restoration of local native ecosystems in cleared agricultural areas (or *environmental plantings*) under different climate and economic scenarios. This module is intended to inform policies such as targeted incentive schemes where payments are made to encourage conservation covenants on existing habitat and the reforestation of agricultural land. Cost-effectiveness analyses compare the relative cost of an action to the outcomes or effects derived from that action and are particularly useful when these outcomes are not defined by monetary value. Similar approaches have been used to identify cost-effective conservation strategies for biodiversity and other ecosystem services (e.g. Bryan and Crossman, 2013; Crossman et al., 2011a). Here we calculate the cost of conservation actions as the incentive payment I required to promote conservation of remnant natural land and ecological restoration with environmental plantings in cleared land as the difference between the economic returns to agriculture $\pi_{s,p,c}^{AG}$ and those to biodiversity conservation $\pi_{s,u,c}^{EP}$.

$$I_{s,p,c,u} = \pi_{s,p,c}^{AG} - \pi_{s,u,c}^{EP}$$

Equation 3

The cost-effectiveness (CE) of these biodiversity conservation measures is then calculated for each climate scenario as the ratio of the incentive payment (i.e. cost) to a biodiversity priority score (i.e. effects) (\mathbf{b}) for each climate scenario. The biodiversity priority score is a measure that quantifies which areas in the landscape provide greatest biodiversity outcomes. The most cost-effective areas for investment in conservation and reforestation through a payment are those with a low CE (i.e. a high biodiversity priority score and a low incentive payment required).

$$CE_s = \frac{I_{s,p,c,u}}{b_s} \quad \text{Equation 4}$$

2.2.4. Weed management – risk analysis

The Weed Management module uses a risk analysis framework to identify areas for targeting weed management efforts under different climate and economic scenarios. Weed risk is evaluated by combining spatial layers of the likelihood of weed invasion with the potential consequence of that invasion. The potential consequences of invasion may be economic, as with agricultural land, or ecological, as with remnant natural land. Areas of high risk will be those with a greater likelihood of occurrence for selected weed species and also a high agricultural or ecological value. A weed invasion likelihood layer \mathbf{l} is calculated under different climate scenarios s as a weed hotspot layer by summing the habitat suitability \mathbf{d} for each weed species w in the set of selected weed species W .

$$I_s = \sum_{w \in W} d_{s,w} \quad \text{Equation 5}$$

A risk layer \mathbf{R} is then calculated as the product of the likelihood (weed hotspot layer) \mathbf{l} and the potential consequence of weed invasion \mathbf{k} . For agriculture the consequence layer could be the productivity, or any of the economic layers derived from productivity, whereas for conservation the consequence layer is the biodiversity priority layer.

$$R_{s,p,c} = I_s \cdot k_{s[p,c]} \quad \text{Equation 6}$$

2.3. Online interface

We implemented each of the four planning modules described above in an online interface. Within the online interface, users have the choice to select from each of the four modules and while working within a module can select any combination of relevant climatic and economic scenarios. A range of relevant maps based on the selections are displayed on the screen and the user can also view relevant statistics. The interface provides geographic information system (GIS) functionality that allows users to visualize, explore, integrate, and interrogate the information within each module and a range of primary spatial datasets (Fig. 6). These tools include:

- Panning and zooming tools so that datasets can be explored at different geographic scales and extents
- An identification tool that facilitates data queries, enables different elements to be identified, and lists their attributes
- A selection tool that allows for individual elements within the scene to be selected and highlighted while multiple elements can be grouped and their attributes summarized.
- A dynamic buffer tool provides for the creation of distance buffers around regions of interest to identify elements with specified distances and summarise their attributes.
- An export function that enables maps and report summaries created within the interface to be exported to PDF and viewed in other media.

The primary datasets such as satellite imagery, remnant vegetation, land use, land tenure, and ancillary data (roads, towns, etc.), provide geographic context and are relevant across all applications. This information can be visualized and explored within the interface and can support analyses within each of the modules.

The web-based interface for the tool was built on HTML 5 and CSS3. The application has a three-tiered structure consisting of a data tier, an application tier, and a web tier (Fig. 7). The data tier provides approximately 17 GB of raster data (approximately 3000 layers) and 50 MB of vector data, as well as non-spatial statistical

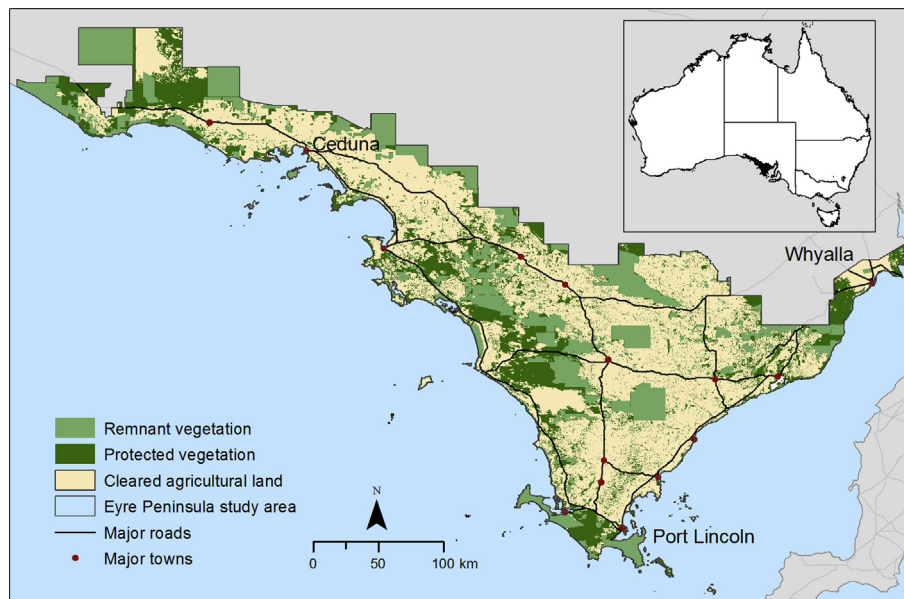


Fig. 1. The Eyre Peninsula region.

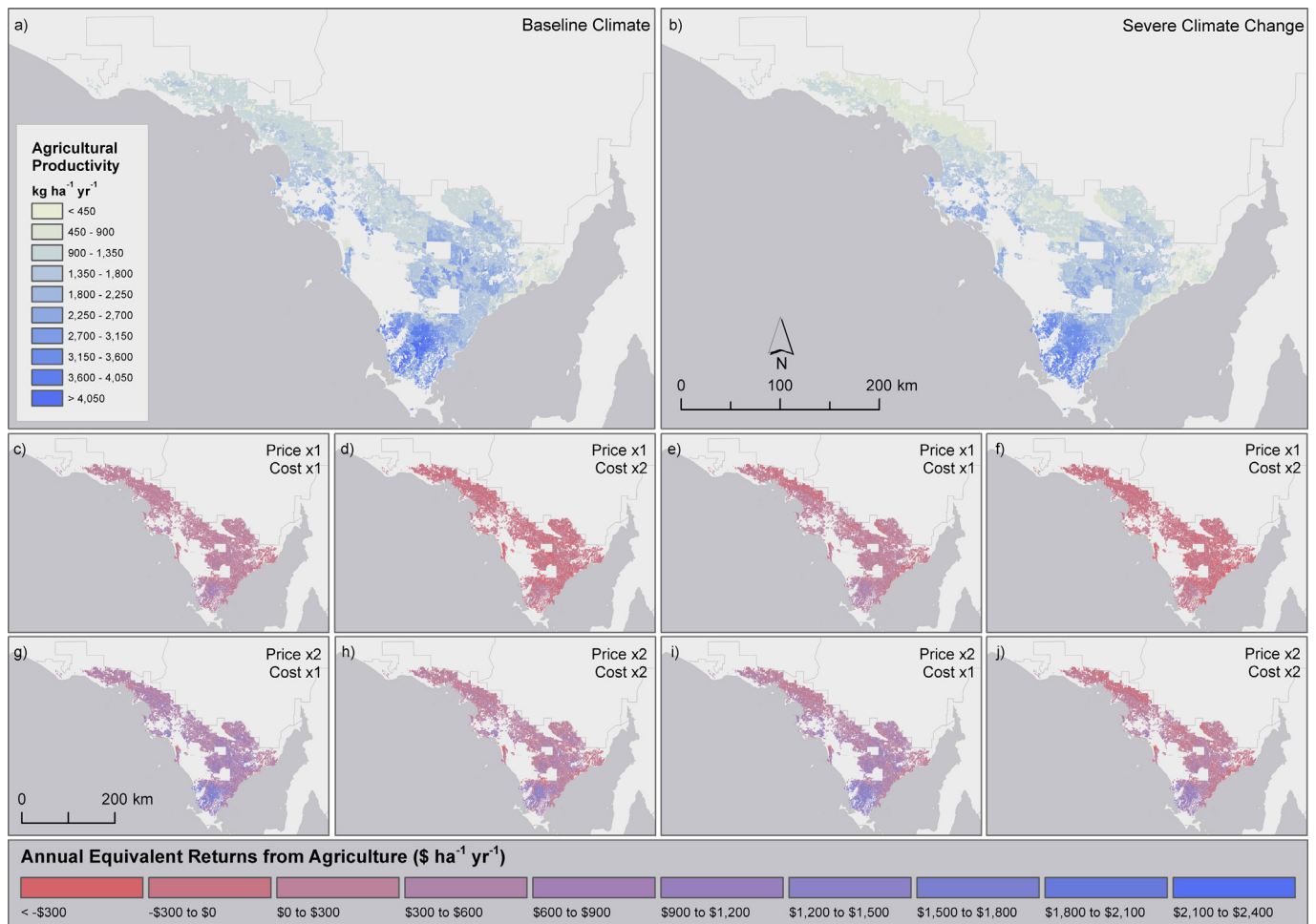


Fig. 2. Agricultural production modelled using the Agricultural Management module under the current climate (a) and under the severe climate scenario (b). Annual equivalent returns under the current climate estimated using the 1.0× cost and 1.0× price multiplier (c), 1.0× price and 2.0× cost multiplier (d), 2.0× price and 1.0× cost multiplier (g), and 2.0× price and 2.0× cost multiplier (h). Annual equivalent returns under the severe climate scenario estimated using the 1.0× cost and 1.0× price multiplier (e), 1.0× price and 2.0× cost multiplier (f), 2.0× price and 1.0× cost multiplier (i), and 2.0× price and 2.0× cost multiplier (j).

information. The application tier leverages ESRI's ArcGIS Server 10.1 to deliver all information to the client via RESTful web services (Adamczyk et al., 2011). Each of the different modules draws on the three tiers to different degrees. The Agricultural Management and Biodiversity Conservation modules involve the selection and display of raster data layers in the web interface based on user choices (e.g. scenario, carbon price). However, the Carbon Sequestration and Weed Management modules involve custom-built, on-the-fly geospatial analyses based on user selections. These custom analyses were written in Python 2.7. The web tier leverages MVC 4 (Microsoft, 2012) and KendoUI (Telerik Inc, 2013) which enables a secure, lightweight client that encapsulates data and behaviour into the view model. This provides a clean foundation on which to build a sophisticated user interface that is extensible but does not require excessive event handlers or document object model updates.

3. Model implementation and results

We undertook a case study to demonstrate the implementation and application of the simple models for communicating complex information to support regional management in the 55 000 km² Eyre Peninsula region in South Australia (Fig. 1). The climate is Mediterranean with rainfall ranging from 250 mm yr⁻¹

in the north and north-west to more than 500 mm yr⁻¹ in the south. The major land use in the region is rain-fed cereal cropping with some sheep grazing. Remnant natural land covers approximately 45% of the study area, comprises ecologically-important mallee woodland communities, and is home to 41 threatened plant and animal species (DSEWPC, 2011). Approximately half of the remnant natural land is protected in reserves or natural heritage agreements.

Below we detail the data used to parameterize each module. We also provide worked examples to illustrate typical outputs and comparisons of selected scenarios. All outputs available within each module are presented in the [Supplementary Material S5](#).

3.1. Scenarios

We specified four climate scenarios following Bryan et al. (2011). Recent historical mean annual temperature and rainfall layers were modelled using ANUCLIM. Adjustments to these layers were made according to the climate change scenarios (Table 1). These scenarios are based on climate change modelling for southern Australia (Suppiah et al., 2006) and represent feasible climate futures covering a range of possible outcomes rather than specific likelihoods or timeframes.

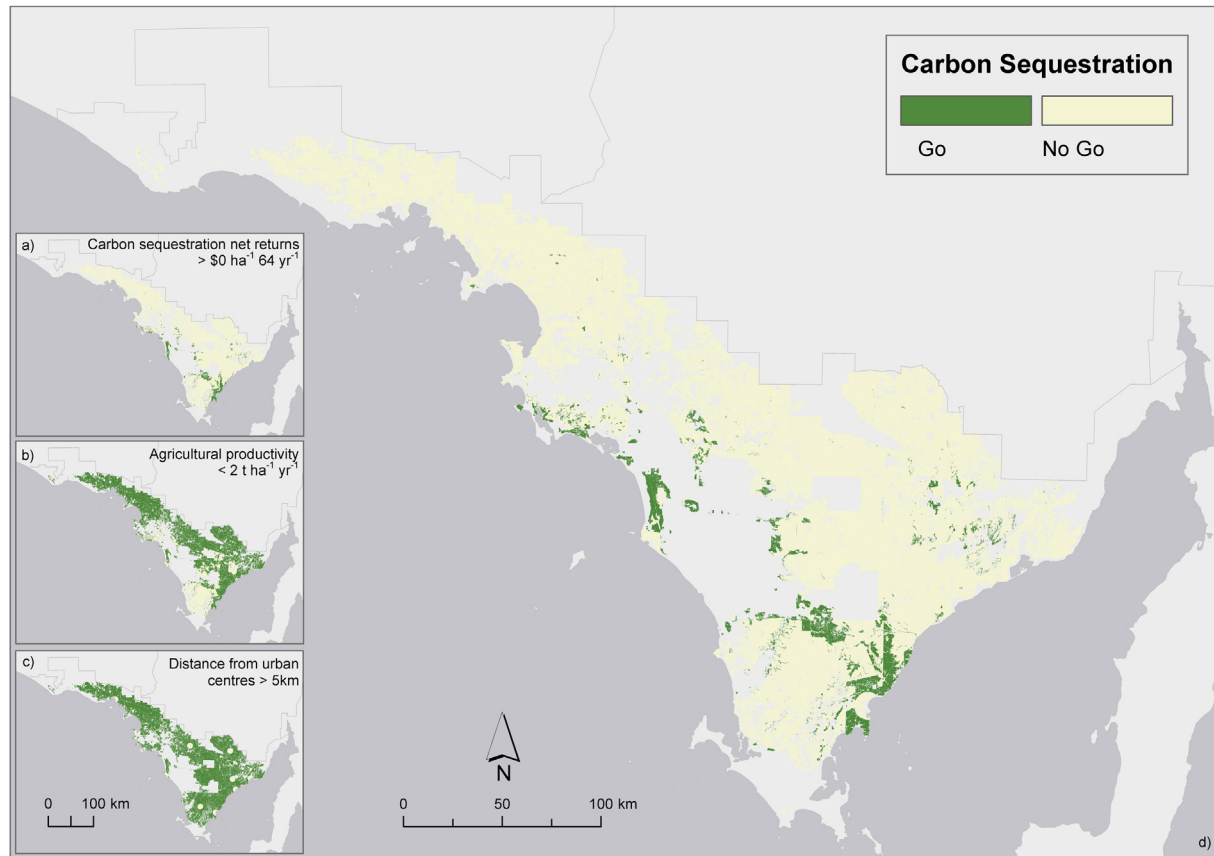


Fig. 3. An example demonstrating the identification of *go* and *no go* areas using the Carbon Sequestration module. Spatial criteria include (a) areas where carbon sequestration net returns $> 0 \$ \text{ha}^{-1} 64 \text{yr}^{-1}$, (b) areas with agricultural productivity $< 2 \text{t wheat ha}^{-1} \text{yr}^{-1}$, (c) areas $> 5 \text{km}$ from urban centres. (d) multi-criteria analysis output with final *go* and *no go* areas.

Baseline ($1\times$) agricultural price data was derived from MLA (2012) and ABARES (2010) and production cost data from gross margins handbooks (Rural Solutions SA, 2012). Production cost data was assembled for three distinct production zones across the study area. Commodity price multipliers were applied to these baseline values (Table 2). Carbon prices were specified to provide a range of plausible values (Paterson and Bryan, 2012), consistent with previous studies (Bryan and Crossman, 2013).

3.2. Agricultural production

The Agricultural Production module allows users to examine projected agricultural production under recent historical (termed *current*) climate and three potential warming and drying scenarios (Table 1), as well as four commodity price scenarios and four production cost scenarios (Table 2). The Agricultural Production SIMulator (APSIM) was used to simulate potential agricultural production under the current climate and the three climate change scenarios. APSIM is a crop growth and agricultural systems model (Keating et al., 2003) that has been used extensively to model agricultural production under various management and climate conditions (Asseng et al., 2011; Bell et al., 2011; Bryan et al., 2010; Luo et al., 2005a, 2005b; Zhao et al., 2013). Here, the modelled yield values were used to populate the profit function and explore the economic returns from agriculture under different commodity price and production cost scenarios. A comprehensive description of the APSIM methods is provided in the Supplementary Material S2.

In the example below we illustrate the use of the model results by comparing two commodity price scenarios ($1.0\times$ and $2.0\times$,

Table 2) with two production cost scenarios ($1.0\times$ and $2.0\times$, Table 2) derived from agricultural productivity layers modelled under the current climate and the severe warming and drying scenario. Annual agricultural yields under the current climate (Table 3, Fig. 2a) were higher than those under the severe warming and drying scenario (Table 3, Fig. 2b). Under both climate scenarios production levels varied substantially with soil and climate conditions. There was a decreasing yield gradient following decreasing rainfall and increasing temperature from the south to the north. There was also a localised yield gradient in the central east of the study area where local topography generates higher rainfall. Productivity along the west coast was low—while the rainfall is slightly higher due to prevailing low pressure systems, it has lower soil fertility. Comparison between the current climate (Fig. 2a) and severe climate change (Fig. 2b) scenarios shows localised changes in agricultural production with lower rainfall areas in the north of the study areas and along the eastern coast of the peninsula demonstrating the greatest reductions under the warming and drying scenario.

Economic returns to agriculture in the study area varied with yield, production costs, and commodity price. Lower and higher commodity prices interact with lower and higher production costs in affecting economic returns to agriculture (Table 3, Fig. 2). The highest annual equivalent returns (AER) (Table 3) were achieved under high commodity prices and low production costs under the current climate (Fig. 2j) and severe climate scenario (Fig. 2i). Alternatively, the lowest economic returns (Table 3) were found under low commodity prices and high production costs for both climate scenarios (Fig. 2d and f).

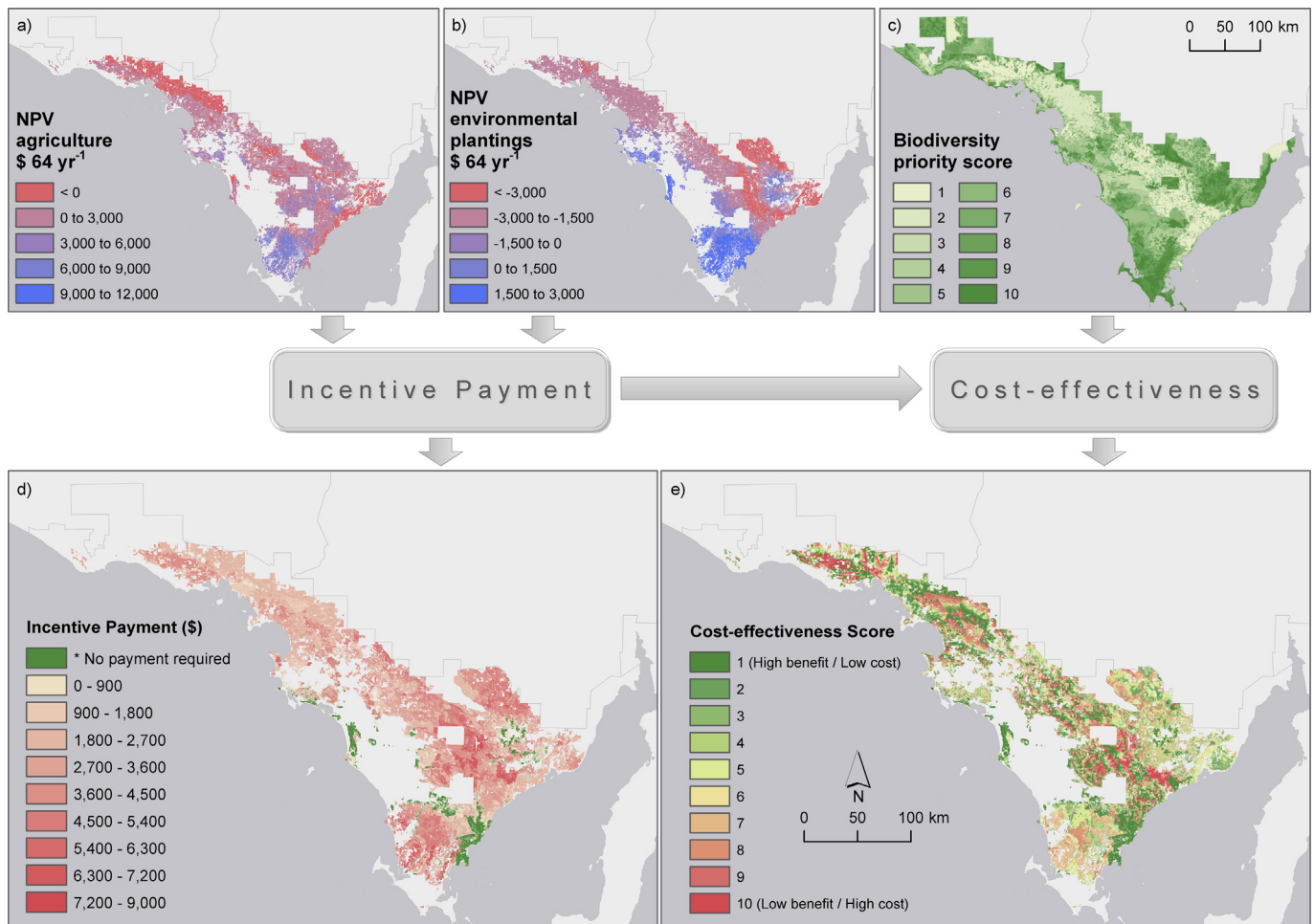


Fig. 4. An example showing the typical work flow using the Biodiversity Conservation module. (a) NPV for agriculture, (b) NPV for environmental plantings, (c) biodiversity priority score, (d) incentive payment and (e) cost-effectiveness score under the severe climate change scenario and 1.0× cost and 1.0× price multipliers.

3.3. Carbon sequestration

The Carbon Sequestration module was designed around a spatial multi-criteria analysis where the user can identify areas suitable for carbon plantings (*go*) and areas that are not suitable (*no go*) according to a range of spatial criteria. A number of layers were assembled and modelled for use as spatial criteria in the study area. Forest growth and the carbon sequestration potential of carbon plantings were modelled using the spatial version of 3PG-2 (Physiological Principles to Predict Growth). This is a process-based model (Landsberg and Waring, 1997) commonly used to predict tree and forest growth for a range of species (e.g. Almeida et al., 2004; Paul et al., 2008) under different climate, soil, and management conditions (Crossman et al., 2011a; Paterson and Bryan, 2012; Paul et al., 2013a, 2013b). We used 3PG-2 to model fast growing monocultures suitable for carbon plantings under the four climate scenarios. Economic returns from carbon sequestration were calculated under the four production cost and carbon price scenarios (Table 2). A range of other criteria were also modelled for identifying *go* and *no go* areas including: agricultural productivity, fire risk, wetlands, salinity risk, soil erosion risk, and ground water recharge potential. A detailed explanation of these methods is provided in the Supplementary Material S3.

In the example below, we specified that areas suitable for carbon plantings (i.e. *go* areas) had net positive economic returns (i.e. returns from carbon sequestration are greater than those from

agriculture; Fig. 3a) and were not prime agricultural lands (i.e. agricultural yields <2.0 t ha⁻¹ yr⁻¹; Fig. 3b). The example is for the severe climate change scenario S3. We also excluded areas with a high fire risk (i.e. areas <5 km from built up areas (Fig. 3c)).

The spatial multi-criteria analysis (Fig. 3) identified an area suitable for carbon plantations running from the central east coast to the central west coast. There were also some limited areas in the central west and the north east of the study area. Under our criteria, a total of 148 463 ha (approximately 6.4% of total area) were identified as potentially suitable or *go* areas for carbon plantings, with the potential to sequester a total of 1.2 Mt CO₂ yr⁻¹ at an average of 8.2 tCO₂ ha⁻¹. Conversion of this land to carbon plantings would create a potential loss of wheat production of 187.1 Mt yr⁻¹. The value of this lost production was 1 885 040 \$ yr⁻¹ under the 1.0× commodity price and production cost scenarios. Conversely, 2 164 965 ha (93.6% of total area) were unsuitable for carbon plantations under the specified criteria. These *no go* areas had a potential wheat production potential of 3247.7 Mt yr⁻¹.

In this illustrative example, we compared *go/no go* areas for carbon sequestration under the severe climate change scenario and the 1.0× cost and price scenario. However, comparisons may be made between all combinations of climate, price and cost scenarios. Similarly, any or all spatial criteria can be included in the multi-criteria analysis, with flexibility in the thresholds selected for each criteria.

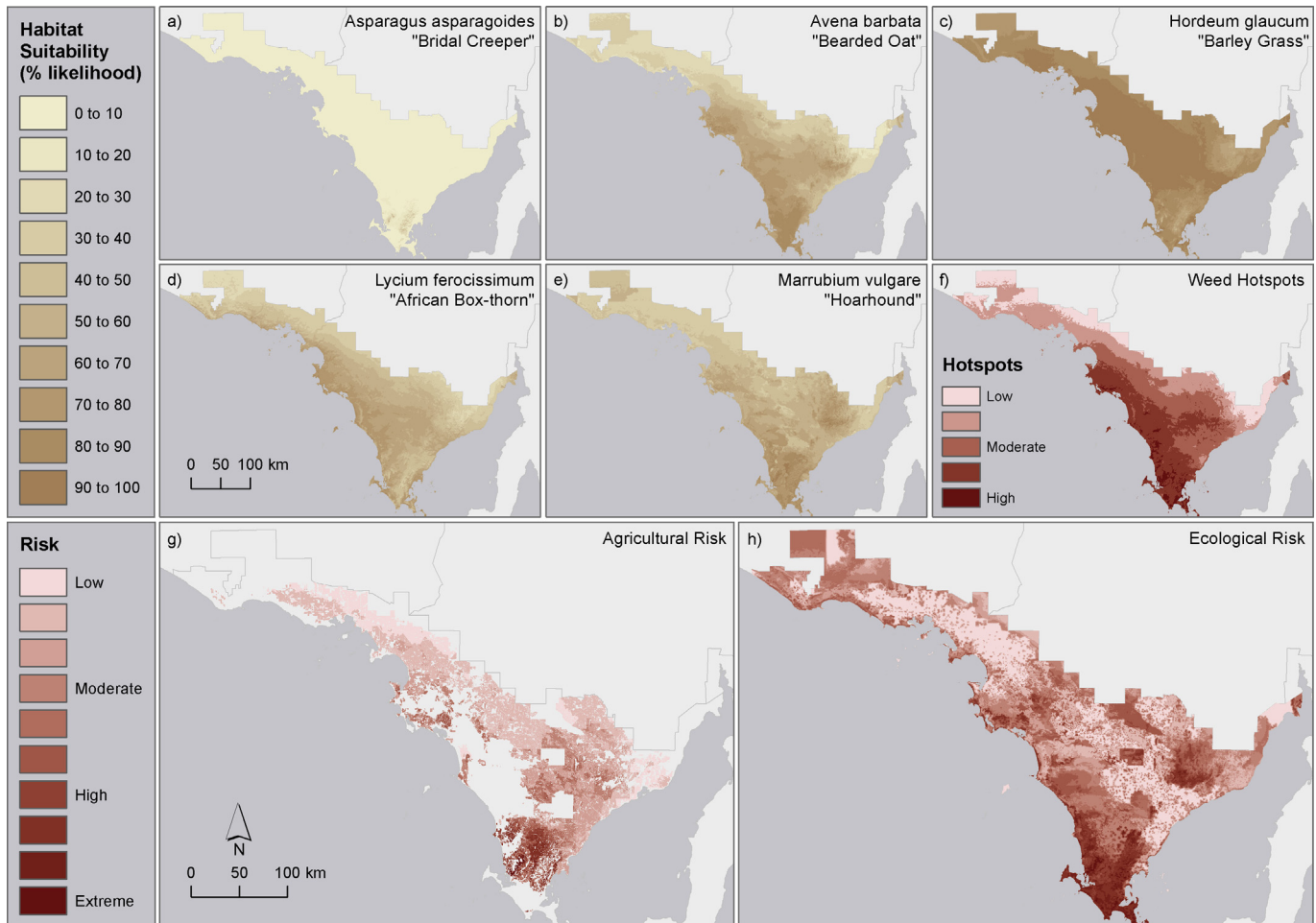


Fig. 5. An example showing the typical work flow using the weed risk module. (a–e) Projected distribution of selected individual weeds under the severe climate change scenario, (f) weed hotspots from combining selected weed species distributions, (g) agricultural weed risk with $1.0\times$ cost modifiers and (e) ecological weed risk.

3.4. Biodiversity conservation

The Biodiversity Conservation module was designed to support spatial planning for biodiversity conservation and ecological restoration by allowing the user to identify the most cost-effective areas for a payment. Outputs can inform investment decisions that are robust to shifts in species distributions, and changes in economic returns to agriculture under alternative future climates and market prices.

In the Biodiversity Conservation module we calculated biodiversity priority scores using species distribution modelling (SDM) and the landscape prioritization software Zonation (Moilanen and Kujala, 2008). SDM uses species location records and their environmental correlates to predict species' distributions in the landscape and then make projections about how they might be affected by changes in environmental correlates (e.g. Coetzee et al., 2009; Pearson and Dawson, 2003). SDMs have been used extensively to explore the impact of climate change on plant species (e.g. Crossman et al., 2011b; Crossman et al., 2012; Summers et al., 2012). Zonation provides complementarity-based conservation priorities and has been used to identify conservation areas based on resilience (e.g. Carroll et al., 2010), cost (e.g. Moilanen, 2007), and vulnerability (e.g. Summers et al., 2012). We used SDM to project the distributions of 286 native plant species under the four climate scenarios. We then used Zonation to combine all of the species distribution layers under each climate scenario into a vulnerability

index that provides complementarity-based conservation priorities for reducing species vulnerability (Summers et al., 2012). A detailed explanation of these methods is provided in the [Supplementary Material S4](#).

The carbon sequestration potential of environmental plantings was modelled using the spatial version of 3PG-2 under the four climate scenarios using the same method as for carbon plantings in the Carbon Sequestration module but using mixed species parameter files rather than *Eucalyptus* monocultures. Economic returns were calculated from the carbon sequestration potential of environmental plantings under the four production cost and carbon price scenarios (Table 2).

In the example below, we identified areas for environmental plantings that maximized biodiversity benefit relative to the cost calculated as a payment for ecosystem services necessary for undertaking environmental plantings (opportunity cost). We illustrate the model outputs using the severe climate change scenario, $1.0\times$ production cost multiplier, $1.0\times$ commodity price multiplier, and $30 \$ \text{tCO}_2^{-1}$ carbon price combination.

We quantified the economic returns in net present value (NPV) terms (Fig. 4a) from existing agriculture and from carbon sequestration from environmental plantings (Fig. 4b). The NPV for agricultural production ranged from $-3792 - 10\,148$ (median 1444) $\$ \text{ha}^{-1} \text{yr}^{-1}$ while that for environmental plantings was $-3695 - 2433$ (median -1501) $\$ \text{ha}^{-1} \text{yr}^{-1}$. We also identified the *biodiversity priority score* across the study site (Fig. 4c). This was derived

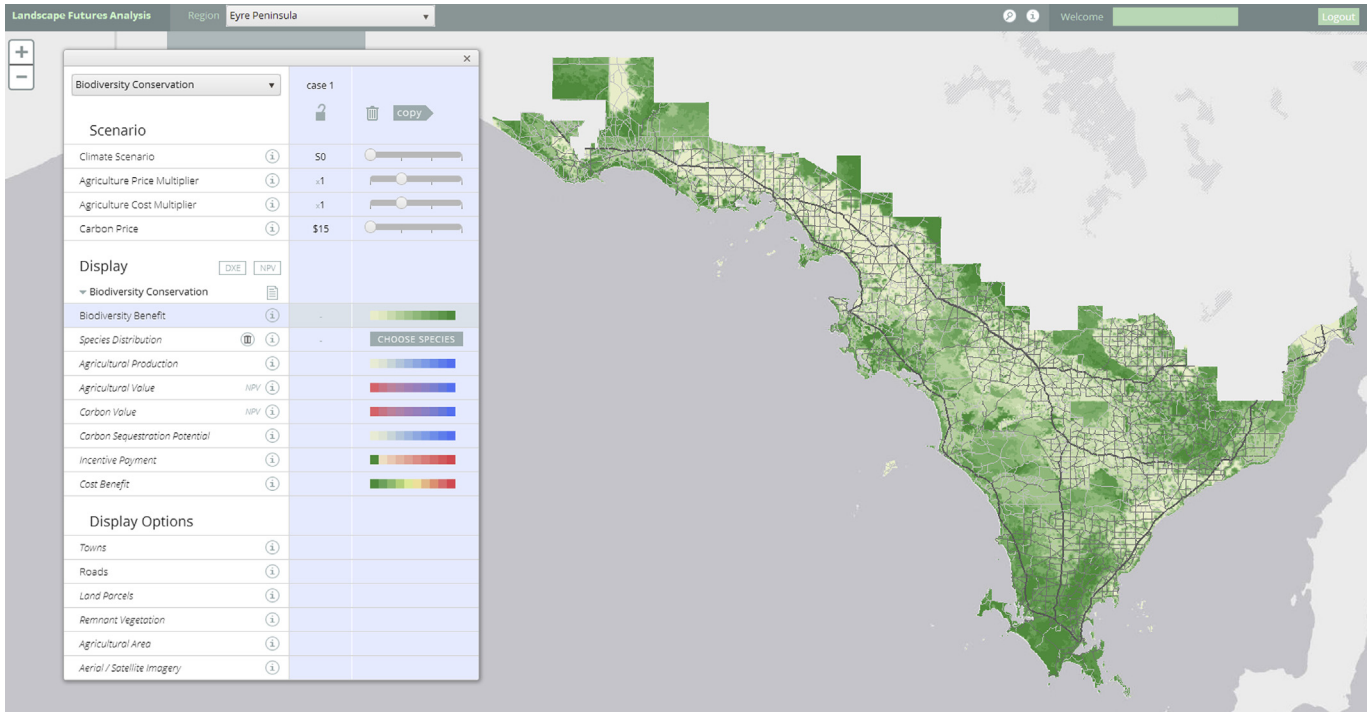


Fig. 6. Screen shot of online interface showing the Biodiversity Conservation module dialogue box and the Eyre Peninsula study area.

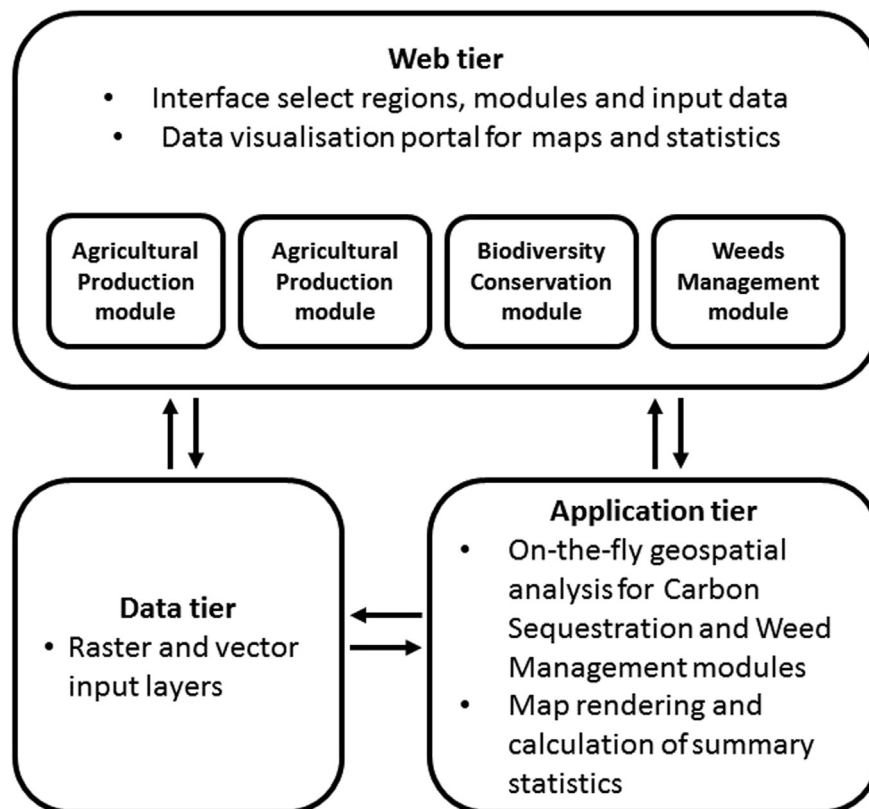


Fig. 7. Flow diagram showing three separate data tiers of the web-based application and their relative functions.

Table 1
Current climate and climate change scenarios used in this study (Bryan et al., 2011).

Scenario	Description	Atmospheric CO ₂ (ppm)	Temperature (°C)	Rainfall
S0	Baseline	390	Historical mean	Historical mean
S1	Mild warming/drying	480	1 warmer	5% dryer
S2	Moderate warming/drying	550	2 warmer	15% dryer
S3	Severe warming/drying	750	4 warmer	25% dryer

Table 2
Agricultural commodity price, production cost, and carbon price scenarios.* Input costs for agricultural production are stratified across three climate zones representing low, medium and high input cost zones (see Supplementary Material S2).

Variable	Units	0.5×	1.0×	1.5×	2.0×
Agricultural price	Wheat price (\$ t ⁻¹)	127.36	254.72	382.08	509.44
Carbon price	\$ tCO ₂ ⁻¹	15	30	45	60
Production cost	Agriculture (\$ ha ⁻¹) [*]	105/158/197	210/316/394	315/474/591	420/632/788
	Reforestation establishment (\$ ha ⁻¹)	1000	2000	3000	4000
	Reforestation annual (\$ ha ⁻¹ yr ⁻¹)	60	120	180	240

from the Zonation landscape prioritization with a high score indicating a high biodiversity priority and a low score indicating low biodiversity priority. In areas where the NPV from environmental plantings was lower than that from agriculture we specified that an incentive payment (Fig. 4d) could be used to promote ecological restoration of agricultural land with environmental plantings. Where the NPV from environmental plantings was higher than agriculture, no incentive payment was required. The incentive payment in this example ranges from 0 to 8422 (median 3041) \$ ha⁻¹ yr⁻¹. Where an incentive payment was required, the *cost-effectiveness score* (Fig. 4e) was calculated as the ratio of the *incentive payment* and the *biodiversity priority score*.

3.5 Weed management

The Weed Management module was designed to explore the potential risk posed by the spread of weeds under changing climates. The user can identify hotspots where there is a high

Table 3
Minimum, median and maximum agricultural production (t ha⁻¹ yr⁻¹) modelled using the Agricultural Management module under the baseline and severe climate scenarios and the respective annual equivalent returns (\$ ha⁻¹ yr⁻¹) using different price (1.0× and 2.0×) and cost (1.0× and 2.0×) scenarios.

		Minimum	Median	Maximum	
Baseline climate (S0)	Production (t ha ⁻¹ yr ⁻¹)	0.28	1.47	4.46	
	Price/cost (\$ ha ⁻¹ yr ⁻¹)	1.0×/1.0×	-264	102	797
		1.0×/2.0×	-658	-146	481
		2.0×/1.0×	-163	448	1951
		2.0×/2.0×	-528	204	1594
Severe climate (S3)	Production (t ha ⁻¹ yr ⁻¹)	0.18	1.29	4.07	
	Price/cost (\$ ha ⁻¹ yr ⁻¹)	1.0×/1.0×	-269	82	720
		1.0×/2.0×	-610	188	404
		2.0×/1.0×	-222	416	1756
		2.0×/2.0×	-538	165	1410

likelihood of weeds occurring under future climates and evaluate the potential consequences of weed species invasion for biodiversity and agriculture. Combining likelihood and consequence layers allows users to explore the potential risk posed by ecological weeds to biodiversity and by economic weeds to agriculture.

In the Weed Management module we used SDM to model weed species distributions under the different climate scenarios. This is the same process used for native plant species in the Biodiversity Conservation module. This provides a probability of occurrence, or *likelihood*, for each weed species under each climate scenario. Agricultural NPV and biodiversity priority layers, developed in the Agricultural Management module and Biodiversity Conservation modules, respectively, were used to provide the economic and ecological *consequence* layers. It is possible to include any combination of up to 55 different weed species known to occur in the study area. A detailed description of these methods is provided in the Supplementary Material S5.

In the example below, we identified spatial priorities for the management of five declared problem weeds under the severe climate change scenario. The selected weed species were; *Asparagus asparagoides* (bridal creeper), *Avena barbata* (bearded oat), *Hordeum glaucum* (barley grass), *Lycium ferocissimum* (African box-thorn), and *Marrubium vulgare* (hoarhound).

Spatial distribution layers for the selected weed species provided a probability of occurrence, or likelihood, for each species within the landscape (Fig. 5a–e). These individual species distributions were combined (by averaging) into a single *weed hotspot* layer (Fig. 5f) which provided the likelihood of invasion or occurrence from low to high. Agricultural and ecological weed risk layers were then created by multiplying the weed hotspot layer with agricultural NPV and the biodiversity priority score, respectively (Fig. 5g and h).

4. Discussion

Here we present the development of the LFAT, an online tool designed to overcome the implementation gap and support management decisions in regional social–ecological systems. In order to bridge the implementation gap, the tool was designed for communicating complex information in a conceptually and physically accessible format. To facilitate this, the four simple models at the heart of the tool were specifically chosen to make the information within accessible to the non-expert. In order to achieve this simplicity, these models were each designed to address a specific planning issue: agricultural production, carbon sequestration, biodiversity conservation and weeds management. The accessibility is further enhanced through the online interface which delivers the information within a self-contained web-based tool providing the functionality of a GIS without the need to purchase expensive proprietary software.

With the Agricultural Management module we illustrated how users can explore changes in yield based on different climate scenarios and also how yields interact with changing commodity price and production costs to affect profitability. This example demonstrates the negative impact that climate change is likely to have on production (Fig. 2a cf. Fig. 2b). However, results from the combination of different economic scenarios indicate that these factors are also likely to play a large role in long term viability of the different land uses. It is clear from comparing Fig. 2c–j, for example, that input cost and commodity price can have significantly greater impact on economic viability. In exploring these different scenarios, end users can understand how these different, and often competing factors interact and use this information to inform planning decisions.

For the Carbon Sequestration module we provided an example that identifies suitable areas for carbon plantings (*go areas*) based on a number of specific spatial criteria. The example demonstrates how users can explore the impact of a range of criteria in the multi-criteria analysis, not only to select final suitable areas (Fig. 3d) but also to understand the impact of each individual component (Fig. 3a–c). The example also demonstrates how users can explore the impact criteria not necessarily related to climate change, production or economic viability directly but that can have important influence on management decisions. This is evident in the example from the inclusion of the criteria ‘distance from urban centres’ (Fig. 3c) which can be an important issue when controlling fire risk for small rural communities. While it was not explicitly covered in the example, this module also allows users to compare relative production levels of agriculture and carbon plantings and the impact of associated economic scenarios. Thus this module allows users to examine the cost benefits and trade-offs of different land use options on the levels of production, economic returns and a range of other social and environmental considerations.

In the Biodiversity Conservation module example we illustrated the calculation of the incentive payment (Fig. 4d) and cost-effectiveness score (Fig. 4e). The incentive payment essentially identifies presence and magnitude of an opportunity cost for using land for environmental plantings rather than existing agriculture. Alternatively, cost-effectiveness distinguishes areas that are most suitable for investment in ecological restoration with environmental planting (low cost-effectiveness) from those that are less suitable (higher cost-effectiveness). This process provides a ranking in the landscape of what areas will provide the most biodiversity benefit for the least monetary cost. Working through the module as we have done in this example, users can consider climate change and market conditions in making restoration and conservation planning decisions.

In the Weed Management module example we illustrated the calculation of a weed hotspot (or likelihood) layer, and its combination with consequence layers to create both agricultural (Fig. 5g) and ecological (Fig. 5h) weed risk maps. The modelled distribution of each individual weed species (Fig. 5a–e) demonstrates how they are each projected to behave differently under the severe climate change scenario. For example, Bridal Creeper (Fig. 5a) is projected to have very small geographical extent while Barley Grass (Fig. 5c) is projected to cover most of the peninsula. The Weed Hotspots layer demonstrates the combined impact of these species, identifying areas of greatest risk as a band from the southern tip of the peninsula through north-west along the coast. These risk areas can be further refined by incorporating agricultural production layers or the biodiversity priority layers, to form the Agricultural Risk layer (Fig. 5g) or Ecological Risk layer (Fig. 5h) respectively. This demonstrates how planners can assess the risk posed by different weeds, identify target areas and develop management strategies as appropriate.

We built these simple analytical models to enable the exploration of some relatively complex regional management issues and we presented this information in a format designed to make this information accessible. There are more sophisticated approaches to many of the issues addressed herein and more complex models that can be employed to provide answers (e.g. Bateman et al., 2013; Bryan and Crossman, 2013; Bryan et al., 2011; Davies et al., 2013). However, to facilitate conceptual and physical accessibility, in order to overcome the implementation gap, we tried to maintain the simplicity of both the modelling and the interface through which it is delivered. One option for example, may have been to integrate outputs from the individual simple models into a single output layer. However, we felt that this would increase the complexity significantly without necessarily improving the desired outcome: a

simple and accessible tool to bridge the implementation gap and deliver natural resource science to decision making. We designed this tool to support regional managers, policy-makers, and planners who need the ability to explore alternative landscape futures and to support decisions with long term consequences. While this approach does include compromises, it provides for the delivery of science to people who otherwise were unlikely to use it, made the information accessible, and thereby facilitated its use in supporting decisions (Hajkowicz et al., 2009).

An important aspect of the development of these simple models and the LFAT was an extensive process of community engagement and consultation. This enabled the developers to build trust with regional planners and decision-makers which was essential for establishing and maintaining credibility in the science. Through this process a mutual understanding developed between the developers and users that intern fostered ongoing discussions and further refinement the LFAT. Similarly, uptake of the tool required capability development for users. The LFAT incorporates a range of technical concepts, data, and analytical capabilities that require some knowledge and skill to effectively manipulate and interpret. This requires training to maximize the utility of the tool and prevent misuse of outputs. Also, while there was significant consultation during tool development, training sessions and roll out has facilitated increased user understanding of the tool capabilities and the nature of the underpinning data and analyses. This generated additional demand for improved functionality to provide a tool that better fulfils the needs of regional planners and decision-makers. This ongoing exchange between developers and users has resulted in substantial ongoing co-learning with the final outcome being a much better tool that is more likely to be used.

As is typical with landscape-scale modelling there are limitations with the outputs and the simple models in the LFAT need to be used with these in mind. All of the modelling presented in the LFAT is intended for regional planning and was not designed to address planning issues at finer scales. An important caveat also needs to be placed around outputs from the web-based tool. The models produce the results of scenario analyses—not projections or forecasts of actual futures. They are not intended to provide a single answer to form the basis of policy. Rather, the process of interaction with model inputs and outputs was designed to increase understanding of complex social–ecological processes and facilitate discussion by enabling exploration of the potential impact of management alternatives and the influence of future changes in environmental and economic drivers (Berkel and Verburg, 2012; Labiosa et al., 2013). Future directions for the LFAT include its application to new regions and new management issues, and the development of new analytical models. We have also applied the LFAT to the Murray–Darling Basin region in South Australia and aspire to extend the tool to include other regions within Australia, and internationally. Application in new regions characterized by different social–ecological systems would require the tailoring of modules that explore relevant regional management issues. The LFAT would be particularly useful in participatory scenario development (e.g. Holman et al., 2008), where it could help explore issues of food security (e.g. Chaudhury et al., 2013), particularly with a focus on irrigated agriculture (Crossman et al., 2010). Other prospective regional management issues include bioenergy planning (Bryan et al., 2010), water quality and environmental flow management (Bohnet et al., 2011; Bryan and Kandulu, 2009), and making complex spatial ecosystem services trade-off analyses more accessible (Raudsepp-Hearne et al., 2010). Similarly, there is also scope to include other analytical models relevant to specific management issues including Bayesian belief networks (Landuyt et al., 2013; Murray et al., 2012), cost-benefit analysis (Chee, 2004) and Monte Carlo simulations (Gabriel et al., 2013).

5. Conclusion

Regional environmental management can present complex challenges for decision making that requires understanding of the possible future impact of different decisions under alternative future environmental and economic scenarios. IAM can provide valuable information about potential landscape futures—identifying environmental and economic drivers and quantifying the possible consequences of different policy, planning, and management options. However, despite the utility of IAM, the outputs have often not been widely adopted in regional policy, planning, and management, a problem known as the *implementation gap* in conservation planning. We created the LFAT to bridge this implementation gap; developing simple models for the spatially explicit assessment of four priority NRM issues: Agricultural Production, Carbon Sequestration, Biodiversity Conservation, and Weed Management, and delivering them through a web-based interface. The simple models integrated a range of data layers to facilitate better understanding of complex spatio-temporal trade-offs in a readily accessible format. Through this modelling and the web-based interface we provide a platform to expose planners to scientific information that would otherwise be less accessible when presented in traditional formats such as papers and reports. There is an ongoing process of training and engagement with users to refine and improve the modules which further promotes its use and thereby supports regional policy, planning, and management decisions. Similarly, there is room to extend the planning modules to include new regions, management challenges, and models.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.envsoft.2014.10.002>.

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