Natural capital and native grazing pastoral systems in Australia: A tale of the north and south

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Abstract

Native pastures, and their natural capitals, such as biodiversity and healthy soils, support a diverse range of low input livestock grazing enterprises across extensive pastoral systems around world, including more than half of the Australian continent. Maintaining the financial and productive sustainability of such farming enterprises has always been a challenge in Australia's climate of high inter-annual weather variation so it is highly likely that maintaining these natural capitals will become even more challenging under climate change. Despite the importance of native systems in the Australian context there has been little exploration of the extent to which maintaining or improving natural capital is likely to support agricultural productivity over the long term, even during times of drought. Unfortunately the evidence is clear that many landholders have already lost some degree of native pasture natural capital through shifts in pasture species composition and cover and feedbacks to the natural system. In this paper we use ecological state and transition models to inform an appropriate couple bio-physical and economic model of two Australian grazing systems with important natural capital outcomes to land managers and the wider community: savanna grazing systems in the Great Barrier Reef watersheds and grassy woodlands in south eastern Australia. Our focus is on the private benefits from natural capital and we conclude these are related to the nature of the ecological system and that they are likely to increase under climate change.

Keywords: natural capital, agro-ecological modelling, pastoral systems, private benefits

Introduction

Native pasture production is reliant by natural capitals such as biodiversity[1] and healthy soils underpinning pastoral production across more than 50% of the Australian continent. Livestock production in these landscapes is particularly reliant on maintaining this natural capital or asset base because of the reliance on deep-rooted, native species, as the most reliable and productive pasture species across large areas of highly variable and often low rainfall. Maintaining the financial and productive sustainability of farming enterprises has always been a challenge in Australia's climate of high inter-annual weather variation. This is predicted to become even more challenging under climate change, which includes a changes to medians and seasonality of rainfall, increases in rainfall intensity, and increases in average and extreme temperatures (CSIRO and Bureau of Meteorology 2018). These challenges are representative of challenges facing pastoral production using indigenous pasture in many locations around the world.

A key question for Australian land managers is the likelihood that, and extent to which investment in improving the health of their native pastures may enhance resilience and realise productivity gains and profits over the long-term – i.e. the private economic benefits to pastoral producers. The assumed co-benefits to biodiversity and reduced sediment pollutant exports from managing natural capital are one rationale for analysing production benefits but their specific management is not the key focus in this paper as they are already broadly described elsewhere (see for example McIntyre and Lavorel 2007; Kroon *et al.* 2013).

Modelling Australian production systems is challenging as few authors have examined the benefits of grazing native pastures, and even fewer in an Australian context with a highly variable rainfall from year to year. As we have previously noted, this characteristic of a highly variable rainfall means that models in the Australian context must pay much more attention to the year to year interactions than a simple annual production model would. Furthermore, the response of native pasture systems to additional grazing pressure combined with a climate exhibiting high inter-annual variations is expected to be non-linear over the long-term, even though in the short-term they are seen to vary in continuous and (at least) partially recoverable ways. This contradiction between short-term variation and long-term state change is at the heart of both the management and modelling challenge in these grazing systems. The loss of natural capital elements in the system induces a hysteretic response when recovery or restoration is attempted, whereby the lost natural capital element must be at least partially recovered (i.e. its condition improved) before an increase in the benefit flows from grazing can begin to be recovered.

In this paper we describe the approach and conclusions from an economic assessment of the private values across two case study locations in Australia: one set in Queensland dry

[1] In this paper we use the term biodiversity in a fairly general sense, not in a strict ecological sense. For example we don't specifically refer to genetic or ecological community diversity when we refer to biodiversity. Generally we use the term to infer a diverse mix of native herbaceous plants and to a lesser degree soil biota that are managed in a way which is also likely to support native fauna communities. Where we discuss production trade-offs we also use the term to infer the values that flow from native diversity as well as the intrinsic value of the biodiversity itself.

tropics region near Charter's Towers, with a dominant wet / dry season rainfall pattern; and a second set in the temperate region of south eastern Australia not far from Canberra, with a more even rainfall pattern. We provide an overview of the conceptual and methodological approach employed which employs an ecological state and transition approach to define alternative pasture production states that are then modelled using coupled agricultural production and economic models. We then illustrate the results from the two case study areas and the substantive difference in conclusions for the economic importance of maintaining natural capital in Australian grazing systems.

The paper in structured as follows. In section two we provide an overview of the key attributes of the natural capital modelling problem and our conceptual approach. In section three, we present an overview of the production and economic models is presented inclusive of the way in which the model is parameterised to represent the farm management scenarios modelled, model calibrations (southern and northern) and limitations. In section four we provide summary results from the modelling (full results are available from the authors). A discussion of the key policy implications, caveats and future potential concludes the paper.

Natural capital in a native pasture grazing systems

The importance of native pastures in Australian agriculture – two examples

Grazing is a major consumer of palatable indigenous plants in Australia, accounting for 40 percent of Australia's gross agricultural product (Bell *et al.* 2014). In this paper we focus on two pastoral production systems – grazing in tropical savanna landscapes in northern Australia and in grassy woodlands in south eastern Australia.

Across northern Australia, including the majority of the catchments delivering water to the Great Barrier Reef (GBR), native pastures are the dominant fodder source for grazing enterprises. Queensland's pastoral enterprises contribute almost 40% of the total livestock equivalents (DSEs) present in the whole Australian grazing industry (Bell, Hayes et al. 2014). Across the higher rainfall slopes and tablelands of south eastern Australia native species are prevalent, although they are less common than introduced pastures where higher fertility soils are present (Bell, Hayes et al. 2014). Because of adequate rainfall in the south-eastern region, fertilizers are often applied as single applications to maximise productivity and pastures are sometimes also supplemented by nitrogen fixing legumes (Bell, Hayes et al. 2014). In 2006 livestock generated 58 percent of the agricultural value of this region (Crimp *et al.* 2010).

Governments across Australia have recognised the importance of these systems for different reasons. In GBR catchments, poorly managed grazing systems are a significant source of sediment, with gully and hill-slope erosion amounting to 45% of total anthropogenic suspended sediment loads going in to the GBR (Kroon, Turner et al. 2013). Poor grazing management is also recognised as a key factor in the initiation of streambank erosion which accounts for a further 39% of all suspended sediments reaching the GBR lagoon. Across south eastern Australia native pastures are generally partial remnants of the pre-existing box gum grassy woodlands (BGGW). More than 95% of BGGW ecological communities have been converted for agricultural uses including grazing production (Rawlings *et al.* 2010) and they are listed under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC) and they are high priority areas for biodiversity investment through programs such as the Australian Government's Environmental Stewardship Program.

Pasture dynamics – representing grazing and production interactions over time

The management of pastoral production systems in highly variable climates such as rangelands have long been known to interact with the future productivity of the system in a non-linear fashion. An alternative framing was proposed by Westoby *et al.* (1989) proposed a state and transition model (S&TM) where states have discrete conditions and are self-maintaining. Transitions between states are driven by episodic natural events or management interventions. S&TM are not quantitative models in the classical sense, and are simply meant to allow managers to look for opportunities to intervene in ways that encourage improvement of state which means that it can be difficult to model trajectories and shifts from one state to another (Stafford Smith and Pickup 1993; Stafford Smith 1996). Example S&TM for pasture management systems in northern (Ash *et al.* 1994) and southern (Orr *et al.* 1994) Queensland are illustrated in (Figure 1). Both models represent the grazing system in terms of desirable components (tall perennial grasses, mature timber a1,a4, b1) and undesirable components (annual grasses, thick shrub undergrowth a3,a7,b2, b4).

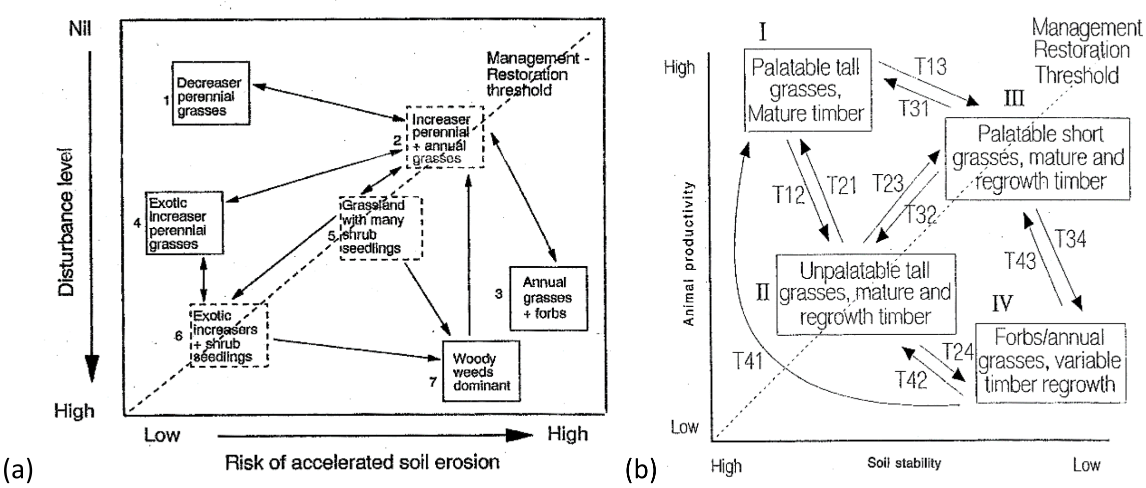


Figure 1: (a) S&TM for the tropical tallgrass lands of Northern Australia (Ash, Bellamy et al. 1994) and (b) S&TM for the southern black speargrass zone (Orr, Paton et al. 1994).
States represented as boxes and transitions represented as arrows. See original papers for a full description of the transitions.

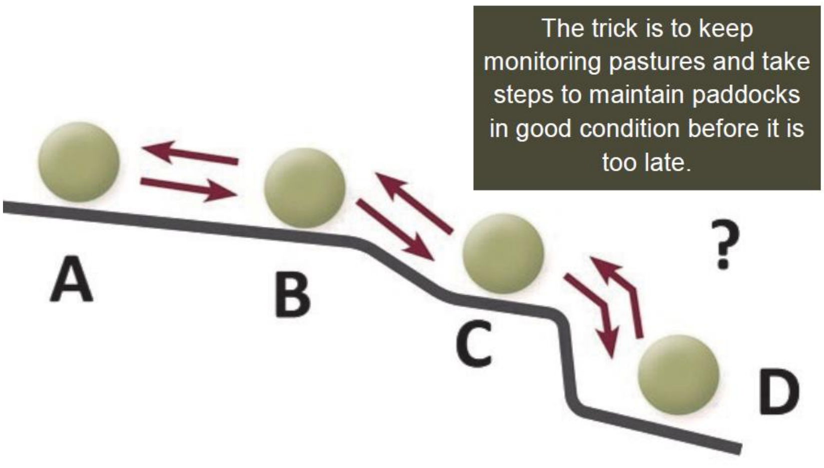
Land condition across watersheds feeding into the Great Barrier Reef lagoon has been defined according to the ABCD construct (Table 1). The ABCD construct is sometimes illustrated using a 'Rolling Ball' model of land condition as illustrated in Figure 2 which seeks to illustrate in an easily communicated way the increasing hysteresis effect as land condition declines (Quirk and McIvor 2003). A substantial proportion of the GBR watershed is regarded as being in a degraded condition (Reef Water Quality Protection Plan Secretariat

2014). That is, we are not focusing on the possibility for future degradation of pasture condition, rather we are starting from an acceptance that much of the landscape is already in relatively poor condition from a native pasture perspective, and are aiming to learn more about the economic attributes involved in improving this condition.

Table 1: Grazing land ABCD land condition indicators

A class grazing land condition	**B class grazing land condition**
Land condition indicators (all indicators at this level): 1. good coverage of perennial, palatable and productive grasses for that land type; little bare ground 2. few weeds and no significant infestations 3. good soil condition; no erosion and good surface condition 4. no signs or early signs of woodland thickening 5. riparian areas in good condition	Land condition indicators (one or more indicators at this level, otherwise similar to A): 1. some decline in perennial, palatable and productive grasses for that land type; increase in other species (less favoured grasses, weeds) and/or bare ground 2. some decline in soil condition; some signs of previous erosion and/or current susceptibility to erosion is a concern 3. some thickening in density of woody plants.
C class grazing land condition	**D class grazing land condition**
Land condition indicators (one or more indicators at this level, otherwise similar to A): 1. general decline in perennial, palatable and productive grasses for that land type; large amounts of less favoured species and/or bare ground 2. obvious signs of past erosion and/or susceptibility to erosion currently high 3. general thickening in density of woody plants.	Land condition indicators (one or more indicators at this level): 1. general lack of any perennial grasses or forbs. 2. severe erosion or scalding resulting in hostile environment for plant growth 3. thickets of woody plants cover most of the area.

Source: Reef Report Card Methodology following Chilcott *et al.* (2005) and McIvor (2012).



The Rolling Ball model of land condition (Quirk and McIvor 2003)

Figure 2: Rolling Ball model of land condition illustrating the thresholds (hysteresis) increasing from B - D

The S&TM concept has not been applied to the same extent in the temperate higher rainfall grazing systems of the southeast of Australia – perhaps due to lower climatic variability and extensive use of sown pastures. Instead continuous succession models still dominate the agricultural view of these grazing systems. But the S&TM concept has been useful for the management of biodiversity conservation in grassy woodland systems (see Yates and Hobbs

(1997), Prober *et al.* (2002), McIntyre and Lavorel (2007), Rumpff *et al.* (2011)). In this project we adapted these management oriented S&TMs to identify agricultural production impacts in a similar way to described for the savanna production systems in the GBR watersheds. We start from a similar assumption – much of the landscape is already in relatively poor condition from a native pasture perspective.

Economic representation of grazing production systems

Although there are a large range of pasture production economics models, few focus on the benefits of grazing native pasture, and even fewer in an Australian context with a highly variable rainfall from year to year. The response of native pasture systems to additional grazing pressure combined with a climate of high inter-annual variations are expected to be non-linear over the long-term, even though in the short-term they are seen to vary in continuous and (at least) partially recoverable ways. This contradiction between short-term variation and long-term state change is at the heart of the management challenge in these grazing systems. The discontinuity in states only occurs after the loss of key natural capital elements through total grazing pressure in excess of that the system can sustain over a period of time. The loss of these natural capital elements induces a hysteretic response when recovery or restoration is attempted, whereby the lost natural capital element must be at least partially recovered (i.e. its condition improved) before an increase in the benefit flows from grazing can begin to be recovered.

Complexity in pasture production economics models broadly spans the following range (see Appendix 1):

- Annual production model: suited to environments with relatively low variability where the same management can be employed in each year (without significant shifts to risks of production in future years). Annual gross margin models with a fixed production or stocking rate without any weather feedback are examples of such models.
- Inter-annual production model: models which include feedbacks across years depending on rainfall and stocking rates are examples.
- Models incorporating some form of hysteresis or phase shift are models in which the inter-annual variation allows the system to shift from one set of production functions to another depending on the initial state of the model, weather and stocking decisions. Some models partially incorporate such feedbacks and, to varying degree, hysteresis.
- There is also a very complex class of socio-economic system models (for example Janssen *et al.* (2000)) developed for savanna rangeland systems which examine multiple enterprise behaviours under a range of ecological parameters and social-ecological system assumptions. These models require substantial effort parameterise and calibrate to the relevant setting and extend beyond the enterprise-specific trade-offs that are the focus in this study.

The key characteristics of a range of models identified from the literature are set out in Appendix 1. Across these studies several trends can be identified. Firstly, relating to the how the biophysical and economic models are combined: whether they employ a coupled biophysical/economic production model; whether rainfall variability is employed (as opposed to averages); and whether there are feedbacks between different years. It follows that a model with no rainfall variability is unlikely to have inter-annual feedbacks. More generally, almost all model applications seek to maintain desirable levels of pasture condition. For example, Janssen, Walker et al. (2000); Müller *et al.* (2007); O'Reagain *et al.* (2011); Ash *et al.* (2015); Jakoby *et al.* (2015) all focus on rangeland grazing and in each case focus on the economic potential of the system subject to maintaining the system in good condition. Janssen, Walker et al. (2000) specifically consider the options for system recovery in the sense that different owners may enter and exit the system, but not in the sense of a choice or a switch in future managements. The approach of MacLeod *et al.* (2004) is the closest to that required across multiple condition states.

Methods

Conceptual approach

The previous section has identified the nature of the challenge in constructing economic models that are able to inform researchers and policy makers about the effects of pasture degradation on enterprise profitability. All pasture production economic models essentially couple a biophysical production model with an economic model. To cope with complexity in our case study systems (and as represented in our conceptual S&TM model) we apply an inter-annual production model which includes a feedback across years depending on rainfall and stocking rates. We also include hysteresis or phase shift across the scenarios which we model (but only partially within our models), in which we characterise a system depending on the initial state of the natural capital base.

The conceptual approach employed across both case studies is set out in Figure 3 .Across the two case studies considered in the project, GBR catchments and BGGW, we are able to draw upon quite different prior research as a basis for our analysis. Therefore, although we are careful to apply parallel approaches, there are some differences in each setting. Necessarily, a range of simplifying strategies are employed in order to make the modelling problem tractable and are available via a detailed report on our modelling methodology (Whitten *et al.* 2019).

The models are implemented using daily time-steps across the time period desired. In implementation there are two primary differences between the typical agricultural economic modelling approach and that implemented in this research. The first difference in implementation is that the starting settings are altered to reflect the different natural capital states that we are modelling. In the northern case study this simply requires a starting land condition to be set within the NABSA model that we adapt for our use. In the southern case study we vary the pasture composition and soil parameters to represent difference states within the S&TM model of pasture condition that underpins our economic model. This is an important step because it allows us to incorporate the impacts of the physical changes that result from a loss of natural capital into our models which then impact on the livestock production outputs.

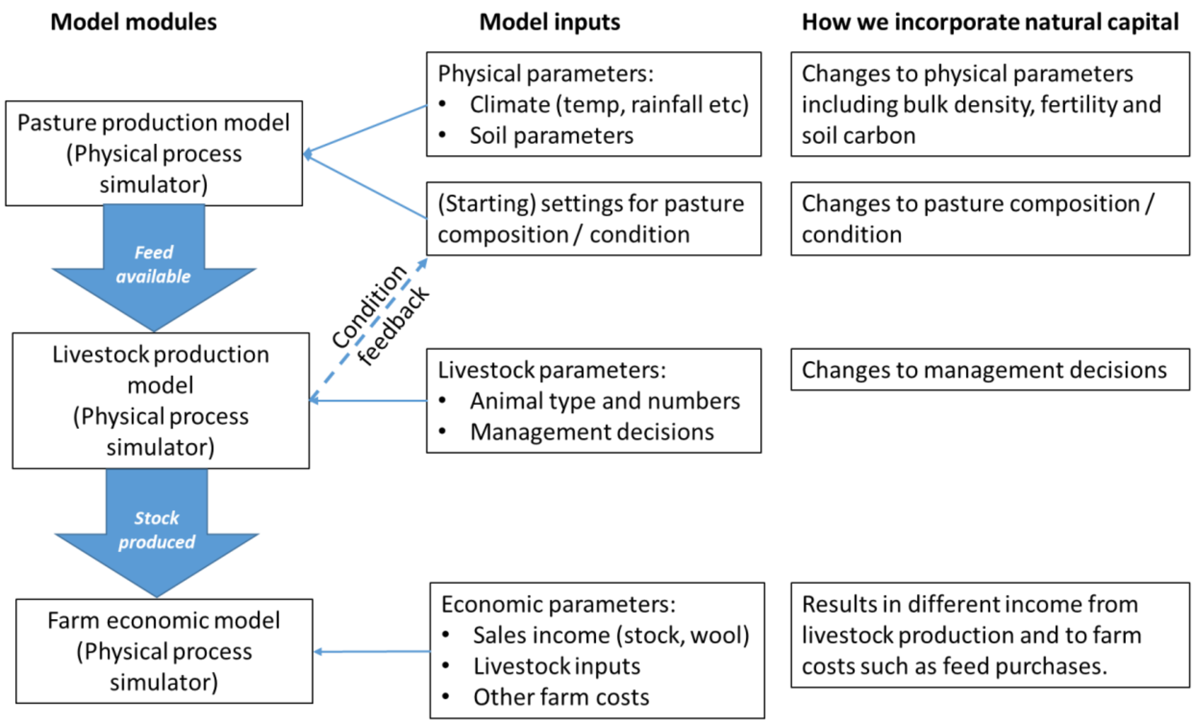


Figure 3: Simplified modelling framework. The left hand column represents the modelling modules. The right hand column the types of inputs required.

The second difference is the feedback introduced between the livestock production model and the starting settings for pasture composition or condition. This step is more explicit in the northern case study where the start condition for each wet season is adjusted dependent on the final pasture condition from the previous dry season. This element explicitly allows the productive capacity of the land to degrade or improve over time depending on whether the natural capital has been drawn down. In essence, if the remaining dry matter at the end of an annual production period falls below a threshold a land condition penalty is applied, and similarly above a threshold a gain in asset condition is applied. The intent of this element is to allow us to calibrate our models to ensure it remains relatively stable under the settings implemented and thus is able to represent the economic outcomes from a particular natural capital state rather than a transition. In the southern model we simply use test runs to ensure that the pasture composition remains stable for the duration of the multi-year model run for production state we are modelling.

Modelling grazing economics in GBR watersheds

In order to explore the outcomes of the complex interactions resulting from changes in northern Australian pastoral enterprise management we needed to couple biophysical models of pasture production and livestock dynamics with economic models of cash flow and financial decisions. A range of models have been developed to explore various aspects of this problem (Mayer 2013), but very few are designed in a way that allowed us to simulate the tropical pastures of northern Australia with climate interactions, allow for managing herd dynamics, and include an economic component with inherent feedbacks that occur as the result of changes in herd management. For this case study we used the North Australia Beef Systems Analyser model (McDonald 2012; Ash, Hunt et al. 2015) from here on referred to as NABSA.

NABSA is a bio-economic simulation model designed to assess the production and financial impacts of incorporating new technologies or management practices within contemporary beef production systems in northern Australia. The model integrates data and output from four separate simulation models: a native pasture simulation model (GRASP); a crop and a forage simulation model (Agricultural Production Systems sIMulator, APSIM); a model for predicting cattle growth; and a model mimicking the economic performance of the crop-livestock enterprise which is calibrated for a given simulation and accounts for labour and farm overheads in tracking pasture state and costs and revenue. The GRASP forage simulation is dependent on a starting land condition that is adjusted via an end-of-season pasture remaining relationship and the APSIM component was not activated in our models.

The model simulations for this case study are based upon the synthetically generated beef enterprise typical of the semi-arid tropics of northern Queensland as parameterised for a previous study (Ash, Hunt et al. 2015) that included validation of the model. That synthetic property was 30,000 hectares with a herd of 2,700 adult equivalents[2] for breeding and fattening. The main target market was steers (450-580 kg) for feedlots or slaughter.

The case study area, was calibrated to be located near Charters Towers (approximately 650mm annual rainfall) across a climate sequence from 1958-2010. The GRASP interface effectively allows the NABSA model to 'lookup' the pasture production for a given year based on the current land condition, climate and stocking rates (utilisation) for any year. This process creates a separation between the NABSA model and the other models such as GRASP. While this provides representative pasture production, there is no direct feedback of management into the other models. The GRASP pasture model was tropical savanna with understorey of predominantly native pasture consisting of tropical C4 grasses. Additional model technical details are available in Whitten, Meier et al. (2019).

The NABSA model modifies the herd size and therefore pasture utilisation through setting the number of breeders retained on farm using purchase and sales rules. The first step in this case study will be to perform simulations to try and attain a constant state across the range of land condition indices given the variability inherent in the climate data. This will provide a number of base states representing the 'states' in our state and transition model from which we can explore the enterprise economics. The herd size was maintained by the purchase and sale of individuals to ensure a set number of breeders were present. This maximum breeder count is the user defined value that ultimately dictates the number of adult equivalents in the herd and is referred to as stocking rate. The following destocking

[2] In our application we vary the initial land condition and stocking rate – thus allowing for different maximum breeder herd sizes on the underlying synthetic property.

strategies were used to constrain herd sizes within biophysical bands and to mimic the impact of different production strategies across different land conditions through time:

1) No destocking: attempts to maintain the breeder herd only through births and the purchase of breeders and sale of heifers as required.
2) Sell steers: Steers were sold below target rate to reduce the herd size. This strategy aims to maintain the female breeders in the herd.
3) Sale of steers and weaners: Scenario 2 plus sale of all weaners (both male and female) in the herd to reduce the herd size.
4) Heavy destocking: Herd reduction by selling individuals in the following order; steers, weaners, dry breeders and wet breeders (>6 years old). This strategy will sell the greatest number of individuals with the greatest chance of preserving pasture, but may require more purchases to maintain the herd when pasture returns.

The model tracks the income and expenditure throughout the simulation and this is then used to compare the financial outcomes of various management strategies. These transactions include farm operating expenses, fees and changes, stock purchases and sales as well as any supplement and feed purchases required. The model also tracks labour expenses.

Modelling grazing economics in grassy woodlands

In contrast to the GBR watersheds case study no existing platform was available for the BGGW case, hence a new model was constructed using the Agricultural Production Systems Simulator (APSIM) soil water, soil nutrient cycling, and surface residue simulation models (Holzworth *et al.* 2014), and the GRAZPLAN pasture and ruminant simulation models (Donnelly *et al.* 2002). The APSIM and GRAZPLAN models were linked using the AusFarm modelling software (Moore *et al.* 2007) so that feedbacks between livestock, vegetation, soil and management could be simulated. The AusFarm modelling software simulates livestock production in terms of meat and wool production, and livestock births, deaths and sales, on a whole-farm basis. This information was linked externally to economic information to enable the calculation of whole farm profit. For each year of the simulation in each scenario, the production information from AusFarm was linked to the income and expenses associated with production to determine the net income for the year. This information can be compared with the equivalent net income from other pasture states to determine the payoff from investment in natural capital.

In the BGGW the APSIM model was calibrated to represent four pasture 'states' which (1) supported livestock production, and (2) had capacity to transition from relatively more degraded states to those in better condition in response to management. The simulated states are defined as (Whitten *et al.* 2016):

- Healthy native pasture that includes high biodiversity: dense, diverse, perennial, and dominated by tussock grasses, although with substantially fewer species than sites without a history of grazing and managed primarily for conservation outcomes.

- Fertilised pasture, in which native species remain but exotic species also occur. This pasture has a more fertile initial condition than the healthy native pasture due to past fertiliser inputs, and supports a higher stocking rate than the healthy pasture.
- Degraded native pasture, dominated by less palatable or grazing-resistant native pasture species and with bare earth between plants. This pasture had a less fertile initial condition than the healthy pasture but was managed in the same way as the healthy pasture.
- Overgrazed native pasture, which had the same initial conditions and pasture species as the degraded native pasture, but which was managed so as to permit stocking pressure to persist at lower ground cover.

We excluded an ‘ungrazed native pasture’ ecological state because it is managed primarily for conservation outcomes and is either infrequently grazed or is ungrazed. We also excluded a more highly transformed comparison, the ‘improved’ pasture state, which supports livestock production through fertiliser application and the predominant use of exotic species which subsequently has little potential transition to the healthy native state.

The BGGW ‘case study’ is calibrated to a model livestock ‘farm’ characterised for a site located within the Box Gum Grassy Woodland (BGGW) community near Boorowa in the temperate region of south-east New South Wales (average rainfall 395 mm) (White *et al.* 2000). Two common soil types were modelled across four pasture states as set out in Table 2. Note that the key difference between ‘Degraded’ and ‘Overgrazed’ is that the ‘Degraded’ state is being managed in a way that is likely to return the state towards ‘Healthy’ over time with an unknown return trajectory.

Table 2: Modelled state set up for grassy woodlands model

Variable	Native pasture state			
	Fertilised	**Healthy**	**Degraded**	**Overgrazed**
Features	*Low-moderate P fertilization (late spring) *C3 dominant *Perennials dominant *Native/introduced pasture species equally	*Diversity of species which grow at different times of the year *Moderately grazed *Low fertility site (no fertilisation at least 30 years) *C3/C4 mix *Perennials dominant *Native species dominant	*High diversity of grazing-tolerant native species *Low fertility site (no fertilisation at least 30 years) *C3/C4 equally *Perennials/annuals equally *Native species dominant	*High diversity of grazing-tolerant native species *Low fertility site (no fertilisation at least 30 years) *C3/C4 equally *Perennials/annuals equally *Native species dominant
Dominant pasture species[1]	*Microleana (25%), Bothriochloa (20%), Rytidosperma (20%),* annual grasses (15%), sub clover (*Trifolium subterraneum,* 20%)	*Themeda* (5%), *tall Austrostipa* (30%), *Bothriochloa* (15%), *Rytidosperma* (15%), *Microleana* (15%), annual grasses (20%)	*Rytidosperma* (15%), *Bothriochloa* (15%), *short Austrostipa* (15%), *Microleana* (15%), annual grasses (40%)	*Rytidosperma* (15%), *Bothriochloa* (15%), *short Austrostipa* (15%), *Microleana* (15%), annual grasses (40%)
Management rules	Destock at <70% ground cover	Destock at <70% ground cover	Destock at <70% ground cover	Destock at <55% ground cover
Return to pasture ground cover (%)	75	75	75	60
Soil fertility scalar	0.85 Chromosol 0.75 Sodosol	0.75 Chromosol 0.65 Sodosol	0.65 Chromosol 0.55 Sodosol	0.65 Chromosol 0.55 Sodosol
Soil bulk density	No change	No change	Increased by 8% (15 cm)	Increased by 8% (15 cm)
Stocking rate (ewes per ha)	4.0 Chromosol 3.0 Sodosol	2.7 Chromosol 2.2 Sodosol	2.7 Chromosol 2.2 Sodosol	2.7 Chromosol 2.2 Sodosol

[1] Selection and proportions based on McIntyre (2008); S. Prober (pers. comm.); P. Graham (pers. comm.).

Results

In this section we describe the core results from the two case studies. Note that the presentation of results does differ somewhat due to the differing model outputs available in each case.

GBR watersheds

The model simulations for this case study are based upon the synthetically generated beef enterprise typical of the semi-arid tropics of northern Queensland as used by a previous study (Ash, Hunt et al. 2015; details in Whitten, Meier et al. 2019). The model employed for the Northern case study was further validated using a multi-step process involving experts and landholders. Simulation results are presented for the historical climate record 1960-

2010. The influence of inter-seasonal variation is illustrated by the range of results shown in Figure 4.

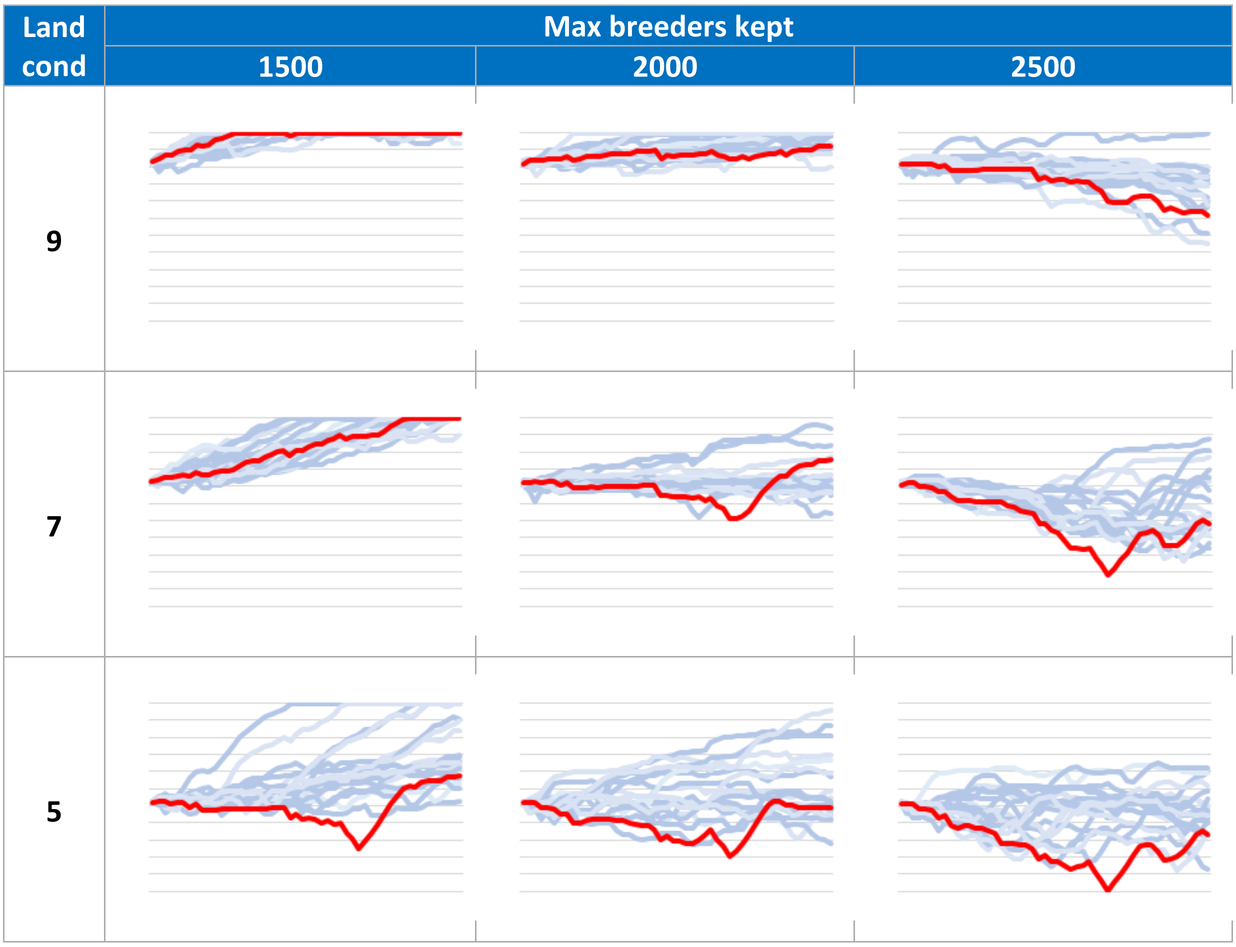


Figure 4: Variation in the land condition between historic rainfall (red) and 19 randomised realisations of the monthly rainfall, breeder destocking

The relationship between the herd size (maximum breeders kept), land condition and the management flexibility employed is illustrated in Table 3. A more aggressive destocking strategy (destocking breeders is more aggressive than destocking weaners than steers than no destock) facilitates maintenance of land condition across a greater range of breeder stocking rates, allowing for a higher target breeding herd size. Target breed herds of up to 2300 can be achieved without loss in land condition for all starting conditions with aggressive destocking.

Table 3: Average land condition index outcome across simulations by destocking scenario.

Strategy Land cond.	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600
	Maximum breeders kept											
No destock												
9	10.7	10.6	10.5	10.3	10.2	9.7	9.3	8.9	8.3	8.3	7.9	7.7
8	10.1	10.1	9.8	9.4	8.9	8.4	7.9	7.6	6.5	6.3	6.6	5.5
7	9.0	8.4	7.3	7.4	6.7	6.3	5.5	5.2	5.2	5.0	4.4	3.8
6	7.2	6.1	6.0	5.6	5.4	5.2	4.4	3.9	4.0	3.8	3.8	3.0
5	4.8	5.0	4.2	3.9	3.4	4.0	2.7	2.9	2.3	2.6	2.3	2.4
Steers												
9	10.7	10.6	10.6	10.5	10.3	9.9	9.7	9.5	8.9	8.4	8.0	7.3
8	10.2	10.1	9.9	9.5	9.0	8.9	7.9	7.2	7.5	7.0	6.5	5.9
7	9.0	8.3	7.8	6.9	7.2	6.9	6.6	5.8	4.9	5.2	4.6	4.6
6	7.2	6.3	6.4	5.9	5.0	4.7	4.5	3.9	3.5	4.2	3.4	3.7
5	5.0	5.1	4.1	4.5	4.6	4.0	3.5	3.4	2.7	3.1	2.6	2.4
Weaners												
9	10.7	10.6	10.5	10.4	10.1	9.8	9.5	9.1	9.0	8.6	8.2	7.5
8	10.3	10.1	9.8	9.5	9.2	8.8	8.0	7.8	7.0	6.8	6.2	6.1
7	9.0	8.2	8.0	7.3	7.1	6.6	5.9	6.1	5.2	4.9	4.8	4.7
6	7.5	7.1	6.2	5.5	5.4	5.6	4.3	4.6	3.9	4.0	3.7	3.0
5	5.9	4.9	4.7	4.4	4.3	3.6	3.3	3.0	3.5	2.7	2.9	2.8
Breeders												
9	10.7	10.7	10.6	10.5	10.3	10.1	9.8	9.4	9.3	8.9	8.8	8.6
8	10.3	10.2	10.0	9.7	9.3	9.0	8.6	8.3	8.0	7.7	7.8	6.9
7	9.3	9.2	8.8	8.2	7.8	7.5	7.0	7.1	6.6	6.9	6.0	6.2
6	8.3	7.7	7.3	7.1	6.9	6.4	6.1	5.6	6.1	5.4	5.0	5.4
5	6.8	7.1	6.3	6.6	6.0	5.9	5.2	5.6	5.5	4.9	4.9	4.6

Notes: Land condition is best =11 and worst = 0, with > 9 = A, 7 = B and 5 = C. Uses the historic rainfall record and 19 random realisations of the historic monthly rainfall. Scenarios resulting in the maintenance of the initial land condition (±0.5) are highlighted in yellow with a decline and improvement highlighted in orange and green respectively.

Targeting higher breeding herd size does come with a financial penalty through incurring greater restocking costs or foregoing potential greater income from sales at greater live-weight as illustrated in Table 4. As a result two key results are illustrated in Table 4. First, higher land condition (A or 9) delivers profits up to an order of magnitude larger than poor land condition (C or 5). Second, maximum profitability is achieved at lower target breeding herd sizes for poor land condition compared to good land condition. Finally, observe that maximum profitability is achieved at herd sizes at or slightly above the maximum size for which land condition can be maintained (with the exception of aggressive destocking). This last conclusion illustrates the challenges of managing livestock in highly variable climates with implications for the future natural capital of grazing lands (see also Appendix 2 showing cumulative frequency distributions of profitability).

Table 4: Average net profit for each scenario (historic rainfall record and 19 random realisations of the historic monthly rainfall)

Strategy	Initial land condition				
Breeders	5	6	7	8	9
No destock					
1700	101,846	408,216	585,785	662,344	625,568
1900	124,996	351,688	616,479	788,566	770,615
2100	99,393	246,294	484,163	781,497	857,361
2300	77,290	162,445	402,616	629,282	893,927
2500	99,244	150,209	382,614	606,942	826,645
Steers					
1700	166,779	408,768	575,399	628,568	659,477
1900	142,472	359,654	627,286	758,750	782,945
2100	142,250	312,327	514,231	751,612	853,332
2300	160,820	196,224	437,261	790,780	992,711
2500	140,362	208,336	455,154	715,969	947,156
Weaners					
1700	160,856	446,986	617,067	642,048	658,399
1900	131,729	364,602	675,765	722,740	789,014
2100	192,635	286,024	530,582	797,818	858,876
2300	150,432	270,054	507,747	748,223	1,006,797
2500	135,795	220,054	440,622	799,294	1,020,601
Breeders					
1700	216,507	499,253	544,616	646,618	643,326
1900	240,421	463,589	636,925	741,096	764,632
2100	206,734	402,072	574,369	868,044	864,979
2300	193,294	374,144	539,737	852,908	957,430
2500	180,399	290,128	494,495	828,933	905,517

Grassy woodlands

Models were parameterised and calibrated to local experience through a schedule of workshops including consultants to producers, Local Land Services staff and land owners (details in Whitten, Meier et al. 2019). Simulation results are presented for the historical climate record 1973-2012 and were also compared to the literature and to local grazing trials. The median monthly biomass of simulated pasture species for the Sodosol soil type are illustrated in Figure 5. In general, the proportion of annual grass is greater in the degraded and overgrazed pasture than other pastures as perennials may be grazed out. Note that total simulated biomass is similar between scenarios because of pasture management rules that resulted in removal of stock at ground cover values of 0.7 (fertilised, healthy and degraded pastures) or 0.55 (overgrazed pasture). The healthy native pasture has a higher proportion of biomass derived from the native species and is assumed to also comprise in small proportions a much wider range of native grasses and forbs representing a higher biodiversity state.

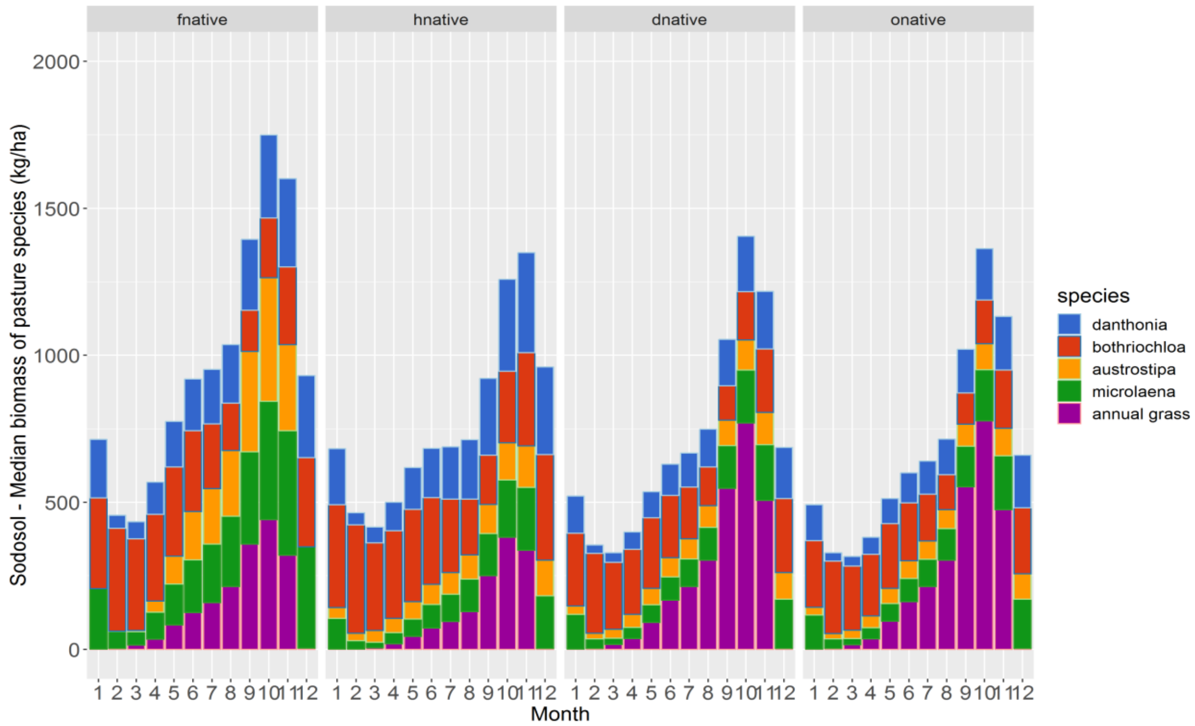


Figure 5: Median monthly biomass of pasture species across ecological states (Sodosol soil type)

Note: Results represent values simulated for the historical climate period 1973 to 2012. Note that for the fertilised pasture that Austrostipa (yellow bars) is replaced with subterranean clover.

The results of the economic models are shown in Figure 6, Table 1 and Figure 7. There are several obvious points that can be drawn from the results. First, fertilised native pastures deliver a higher gross margin than any other state. Farm profitability in sheep grazing enterprises is closely linked to stocking rate (Amidy *et al.* 2017) and so the whole farm profit before tax was greater in the fertilised pasture than unfertilised pastures. Second, the gross margins derived in all ecological states are highly variable through time – driven by climate variability driving available pasture biomass. Since many income items (e.g. wool and lamb sale income) and expense items (e.g. sheep health costs) are directly linked to the stocking rate the standard deviation of net profits from the fertilised native pasture state was also frequently greater than from the other pasture states (particularly on the Chromosol - Table 5 and Figure 7).

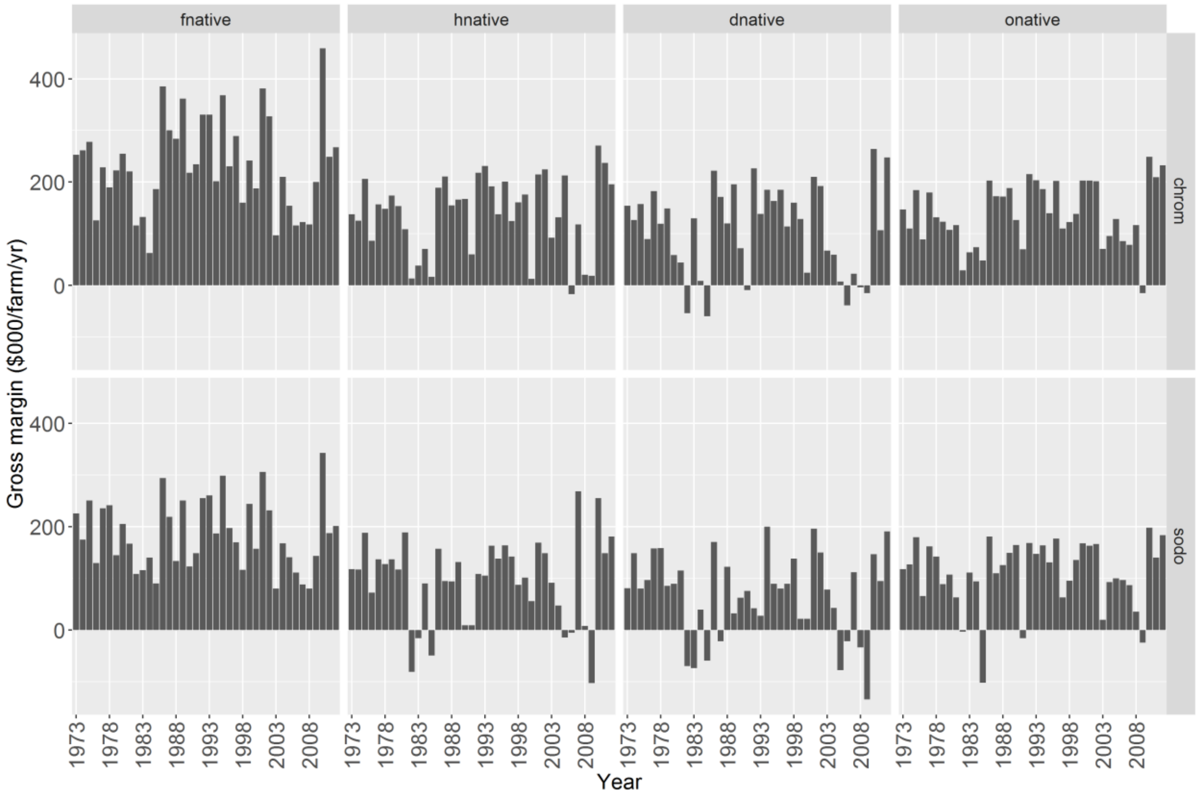


Figure 6: Annual gross margin per hectare by ecological state for model period and soil type Chromosol 'chrom', upper figure panels and Sodosol 'sodo', lower figure panels.

Table 5: Summary measures of annual profit and variability by ecological state and soil type

	Farm net profit before farmer's salary and tax ($ farm^{-1} yr^{-1})							
	Chromosol				Sodosol			
Summary statistic	fnative	hnative	dnative	onative	fnative	hnative	dnative	onative
Minimum	(16,602)	(96,666)	(139,445)	(94,569)	966	(182,311)	(213,672)	(181,494)
Maximum	379,518	191,150	184,839	169,267	263,364	188,794	120,790	118,884
Average	154,383	59,347	28,476	58,298	104,795	18,101	(10,896)	29,926
Median	149,795	74,602	43,451	50,808	92,900	33,174	1,234	41,984
Standard deviation	90,149	74,245	87,026	61,003	67,930	83,033	82,329	65,885
Standard error	14,254	11,739	13,760	9,645	10,741	13,129	13,017	10,417

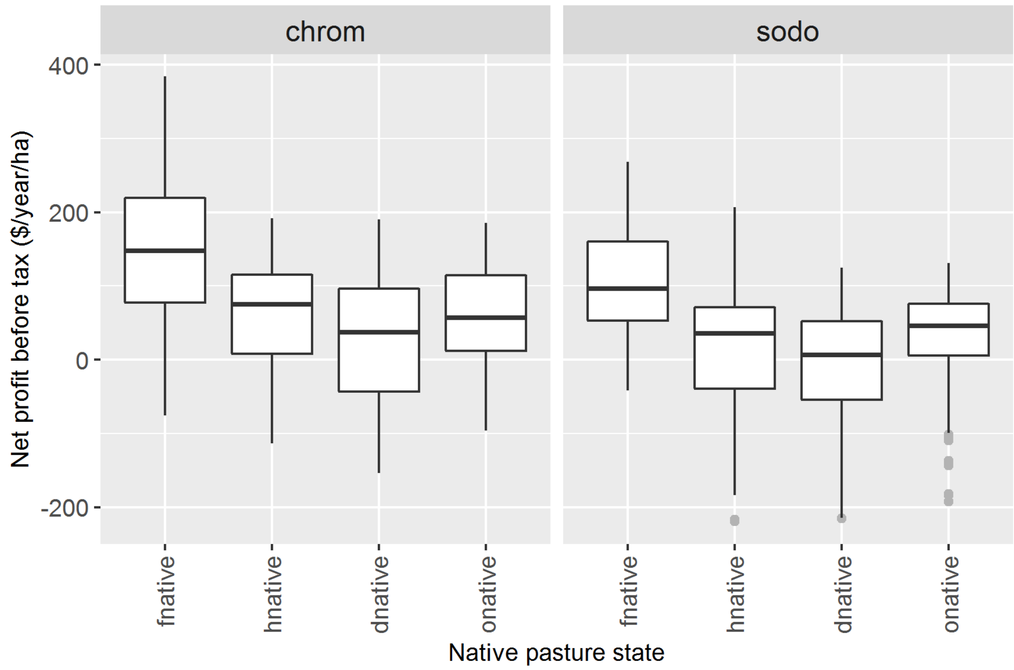


Figure 7: Annual net profit per hectare – grassy woodlands by soil type and ecological state

For the healthy, degraded and overgrazed pasture, the stocking rates were lower than for the fertilised pasture, and so the net profits were also lower than for the fertilised pasture. However, while the healthy and overgrazed pastures had the same stocking rates, there was much greater variability in profits driven by the number of forced stock sales that occurred in the different pastures, in response to attaining the minimum permitted pasture cover. These forced sales attracted a 30% penalty in sale price and a 10% greater repurchase price than for sales and purchases at other times. The Fertilised and Healthy scenarios had similar forced sales but the higher revenue from meat and wool sales in the fertilised state compensated for forced sale losses. In contrast, the difference in management strategies in the degraded and overgrazed states drove a much higher number of forced sales in the degraded setting (incurring a higher penalty) and a less than half the forced sales in the overgrazed setting. Hence the final result, managing native pastures in a conservative way, thus improving biodiversity outcomes, does not appear to deliver a substantive economic benefit. Furthermore, managing 'Degraded' pastures towards a healthy state appears to incur a cost over continuing the 'Overgrazed' strategy (providing there are not additional unaccounted for pasture productivity losses into the future).

Discussion and conclusions

Emergent themes

Across the two case studies the challenges to landholders in maintaining natural capital are evident – albeit in different ways and with different challenges. In the norther savannah pastures setting (GBR watersheds) a strategy to maintain natural capital is financially dominant yet much of the landscape is has been degraded – often beyond a hysteresis point where recovery is slow and uncertain. The driver of lost natural capital appears to lie in the nature of the stocking strategy to profitability trade-off – particularly in a historic setting where it may have been more challenging to forecast feed budgets or more costly to destock. A profit maximisation strategy on land in good or moderate condition leaves little margin for error with respect to loosing land condition. Landholders with the best intentions may make mistakes, and mistakes in this setting can easily have a long-term adverse impact on land condition. Furthermore, loss of land condition has implications for both private and public benefits in this setting: private benefits via reduced profitability and public benefits via increased sediment export which damages the world heritage listed Great Barrier Reef. Finally, once land condition is lost, the cost and uncertainty of land condition recovery make investment risky.

The southern setting is driven by a differing ecological outcome to the north which in-turn drives the nature of the conclusions. As land condition in the north declines from A to C the pasture composition shifts from thick sward of tussocks comprising productive palatable perennials (so-called 'triple P species') towards an annual dominated mix. The annual mix is less productive in total biomass and less nutritious during the dry season (May-November). The temperate setting in the south means that grazing tolerant perennial species remain, albeit with a larger proportion of less productive annual species. Furthermore, landholders are able to adapt to loss of natural capital via a delayed destocking strategy (apparently without further loss to the system which appears stable – although this is not a model output). Furthermore, the effect of a more consistent rainfall and benign seasonal conditions in the southern system means that it may be profitable to input fertiliser and species increasing the biomass production albeit with the loss of biodiversity in the system. Hence, at least in these initial models there appears to be few benefits from maintaining the natural biodiversity in the grazing system.

Climate change impacts on production systems

Our baseline analysis does not admit the reality that climate change has already begun to impact these production systems and which will experience increased effects into the future. Therefore we conducted an exploratory analysis of the likely impacts of climate change on our models in order to assess the degree to which climate change may alter our results. We used three contrasting global circulation models (GCMs) to assess the climate impacts to 2030:[3]

1. HadGEM2-AO with Representative Concentration Pathways (RCP) 4.5 and low sensitivity to CO_2 increases - this model predicted little change in rainfall ($\pm$ 5% change in rainfall) and an increase in temperature of 0.5 to 1.5 $^{\circ}$C;
2. MIROC5 with RCP 8.5 and high sensitivity to CO_2 increases - this model also predicted little change in rainfall ($\pm$ 5% change in rainfall) and an increase in temperature of 0.5 to 1.5 $^{\circ}$C; and

[3] The rationale for the 2030 time limit was that this could be anticipated as an appropriate pay-off timing for an investment now in the recovery of natural capital across our case study areas.

3. GFDL-CM3 with RCP 8.5 and high sensitivity to CO_2 increases – this model predicts a drier future (-5 to -15% decrease in rainfall) and an increase in temperature of 0.5 to 1.5 °C.

Results for the GBR watersheds are shown in Table 6 and Table 7. The results illustrate that climate change has an adverse impact on profitability under each of the three climate models considered. Average profit declines by between three and twenty percent. Profit declines are smallest (indeed likely to be negligible amongst other system noises) for land in good condition – falling between three and five percent.

Table 6: Average net profit ($) for each future climate scenario based on the different initial land condition for all simulations (breeding herds) using the highest destocking strategy.

	Initial land condition				
Climate scenario	**5**	**6**	**7**	**8**	**9**
Current	$205,324	$398,887	$539,175	$720,130	$791,165
GFDLCM3	$188,493	$378,963	$545,390	$670,939	$767,949
HadGEM2AO	$172,953	$355,368	$526,062	$703,756	$763,775
MIROC5	$163,262	$338,678	$491,183	$655,285	$754,374

Table 7: The proportional change in net profit ($) for each climate change scenario from the current rainfall simulations.

	Initial land condition				
Climate scenario	**5**	**6**	**7**	**8**	**9**
GFDLCM3	-0.08	-0.05	0.01	-0.07	-0.03
HadGEM2AO	-0.16	-0.11	-0.02	-0.02	-0.03
MIROC5	-0.20	-0.15	-0.09	-0.09	-0.05

Results under climate change in the grassy woodlands setting are less optimistic showing that on average enterprise profitability is negative under all native pasture scenarios on Sodosol soils and declines substantially on Chromosols. Nevertheless, profits decline by smaller amounts for healthy native pasture (which retains higher levels of biodiversity and thus natural capital) than for degraded systems including degraded systems which are managed more conservatively.

These conclusions illustrates the increasing financial penalty when landholders are forced into more regular destocking under greater climate variability. Our results also illustrate the potential insurance value associated with maintaining natural capital in the face of climate change. Nevertheless our results with respect to climate change should be interpreted with caution because they only partially incorporate the impacts of climate change. First, they do not necessarily take into account the full range of climatic shifts including increasing climate variability or the effects of extreme events. Second, they make no account of landholder adaptation in the face of climate change, which – as we summarise next – is an important driver of our overall results.

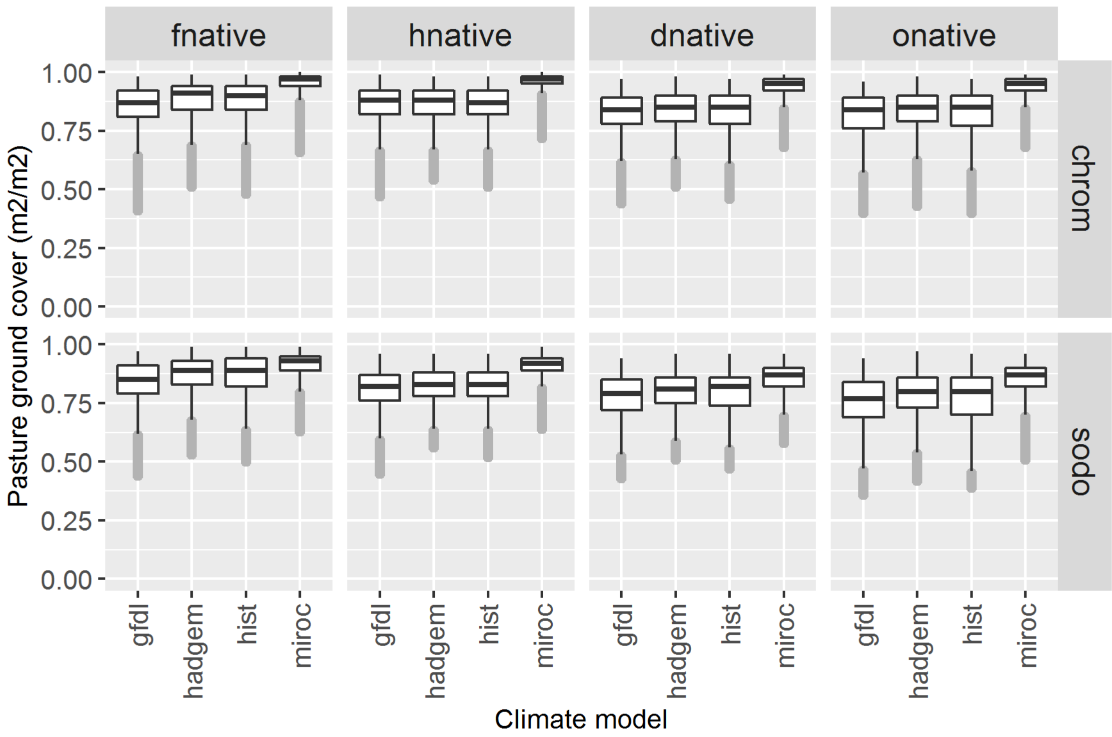


Figure 8: Ground cover in future climates

Notes: Average annual pasture ground cover from green material and plant residues on the fertilised ('fnative'), healthy ('hnative'), degraded ('dnative') and overgrazed ('onative') native pasture states on the Chromosol ('chrom') and Sodosol ('sodo') soils. Results represent values simulated for 40-year based on the historical climate period 1970 to 2009 ('hist'), and projected future climates predicted from four different GCM models (described in the text). Box and whiskers plots represent the median value (horizontal bars in the boxes), the next 25% of values (quartiles) above and below the median (boxes), and 1.5 times the interquartile range (whiskers).

Modelling challenges

A number of challenges arose in developing our modelling framework which are likely to apply in attempting to model the loss of natural capital in other agricultural production settings. Challenges can be divided into three classes: capturing the physical implications of a loss of natural capital within the physical production model; identifying management limitations and the types of adaptation that landholders may employ where natural capital has been lost from a farming system; and finally, the nature of any economic feedbacks which may be linked specifically to different management strategies.

In the case of the native pasture production settings that we are modelling there was no existing pasture production model available for the grassy woodlands setting. Although there was a relatively standard modelling platform available (APSIM) we needed to identify an appropriate suite of pasture species for inclusion from a relatively limited set of native grasses for which growth responses had been parameterised. Furthermore, no previous models had sought to identify what impacts a loss of natural capital from the production system would likely have on soil parameters. Inclusion of these changes were necessary because they alter the overall productive potential of a farm where natural capital has been lost. That is, loss of natural capital is represented the combined change to pasture composition and soil productive capability. This challenge was mitigated in the north where degraded pasture production models were already available.

The second challenge arises in the extent to which the selected modelling platform is able to incorporate the desired set of management parameters. Models are typically designed to provide a representation of a particular operating space, and often do not function well when implemented beyond the originally intended scope. In our Northern case study we found that the model needed to be modified to allow for the suite of management decisions desired. Land managers, as economic agents, are likely to adapt their livestock management decisions to maximise profitability where natural capital has been lost. In both case studies we implement a matrix of management responses where natural capital has been lost to identify the potential impact arising from management adaptation as shown in Table 8. In the south landholders are modelled as adapting via a delayed threshold (lower biomass threshold) for destocking. In the north landholders are modelled as adapting via a variable production strategy switching between weaners and steer sales dependent on feed availability whilst attempting to maintain a larger breeder herd. Complicating modelling further there is the option for many landholders in grassy woodlands to at least modify parts of their production system via the addition of fertiliser and alternative pasture species (usually sub-clover).

Table 8: Management scenarios modelled

Natural capital management	Natural capital condition		
	Good	Poor	Modified capital comparison case
Management that supports natural capital	Modelled in both	Modelled in both	Not applicable (damages biodiversity)
Standard practice management	Not applicable – would degrade system.	Modelled in both	Modelled in south only (improved pasture)

Third, it is inherently difficult to model feedbacks in highly variable systems. As an example consider the herd mix over time illustrated in Figure 9. The system variability exhibited poses two related analytical problems – firstly averages and medians provide little information about the critical pressure points on the system and second the weakness of using standard present value methods to interpret future income streams. In this particular instance there are five consecutive years in which no livestock are present in our enterprise model which is likely to endanger even the most well prepared farm enterprise. In our modelling we have presented averages and distributions where possible but remain cautious as to whether they represent a full picture of the value of natural capital. For example, an enterprise with good land condition and a very conservative stocking rate is barely reduces total stock numbers during the same climate period.

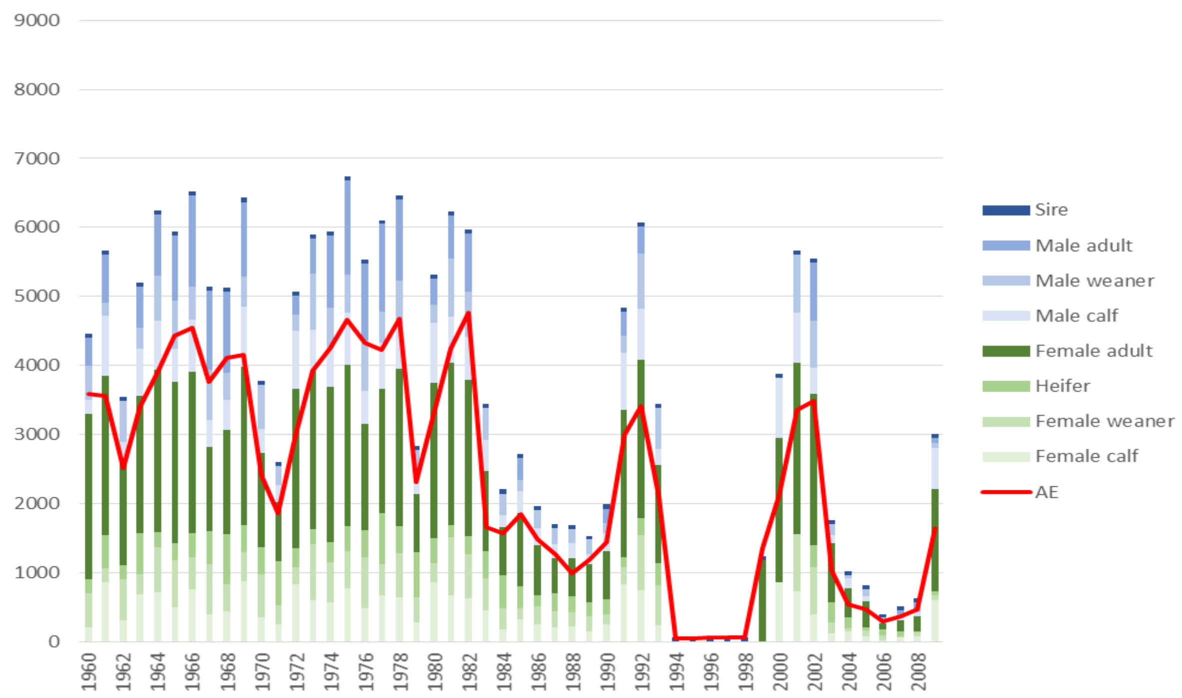


Figure 9: The number of individuals (May) in each population class and the adult equivalents (red line) for high stocking on poor GBR land during the historic rainfall simulations.

Finally, there may be economic feedbacks that result from the management strategies employed. Although these may conceptually be quite complex, their interaction with other factors such as global markets, the extent of drought (and therefore impacts on supplementary feed availability and pricing) and so on make these difficult to define. In our models we limit the economic feedback to a price penalty to forced livestock sales.

Implications for results and future work

The modelling approach set out in this paper is the first that we are aware of which explicitly seeks to incorporate the longer term effects of management of natural capital on the economic outcomes from natural grazing production systems. Our approach is structured to capture the most important elements impacted by a loss of natural capital – namely the change in pasture composition and soil parameters in grassy woodlands, and the equivalent loss of land condition, essentially represented by a shift from productive, palatable, perennial species to annuals, in the northern grazing setting. We do identify a number of limitations which mean that our results should be interpreted with these in mind and illustrate some promising areas for future work.

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Appendix 1: Pasture production economics models reviewed

LITERATURE REFERENCE	PRIMARY FOCUS	COUPLED BIOPHYSICAL MODEL	RAINFALL VARIABILITY	INTER-ANNUAL FEEDBACKS
Ash, Hunt et al. (2015)	Assess the production and financial implications of technology improvements on northern Australia beef systems	Yes	Yes	Yes (no hysteresis)
Foran *et al.* (1990)	Assesses development and management options of rangeland properties in the Northern Territory, Australia.	No	Yes	No
Gregg and Rolfe (2013)	Econometric efficiency frontier analysis on the use of an environmental input. Results suggest less efficient enterprises could benefit from higher groundcover.	No	Yes	No
Gross *et al.* (2006)	Agent-based model designed to illustrate interaction between environmental heterogeneity and manager learning. Focus is on comparative outcomes over time.	Yes	Yes	Yes (partial hysteresis)
Holmes (2015)	Identifies key business drivers of landholder success in rangeland grazing in Australia based on an analysis of enterprise financial data.	No	No	No
Jakoby, Quaas et al. (2015) (model based on (Müller, Frank et al. 2007; Quaas *et al.* 2007))	Ecological-economic spatially explicit model of livestock management to compare different stocking strategies in rangelands finding stocking rule dominates rotation rules.	Yes	Yes	Yes (no hysteresis)
Janssen, Walker et al. (2000)	Agent-based model of multiple enterprises different policy options (including regulated destocking) with agent learning across 200 years with exit and entry.	Yes	Yes	Yes (hysteresis)
MacLeod, Ash et al. (2004)	Representative model of livestock production based on differential pasture conditions simulated over a 100 year climate run.	Yes	Yes	No (pre-existing)
Müller, Frank et al. (2007)	Simulation model of resting in rangelands and which identifies why resting in wet years out-performs resting in dry years.	Yes	Yes	Yes (no hysteresis)
Müller, Frank et al. (2007) (model concept per (Müller, Frank et al. 2007; Quaas, Baumgärtner et al. 2007))	Model analysis of whether the availability of rain-index insurance would affect rangeland management. Conclusion suggests low-medium strike level has a positive impact on farmer well-being without negative sustainability impact	Yes	Yes	Yes (no hysteresis)
O'Reagain, Bushell et al. (2011)	Reports results of a long term (12 year) trial of different grazing strategies in northern Queensland. Included a wet season spelling strategy.	Built in	Built in	Partly built in
Quaas, Baumgärtner et al. (2007)	Ecological-economic model of grazing rangelands with different resting strategies. A sufficiently risk averse farmer can still choose a sustainable strategy.	Yes	Yes	Yes (no hysteresis)
Quaas and Baumgärtner (2012)	Builds on Quaas, Baumgärtner et al. (2007) to differentiate strategy based on existing pasture stocks and rainfall.	Yes	Yes	Yes (partial hysteresis)
Star *et al.* (2015)	Identifies variability in landholder profitability across a climate cycle in Queensland and the link to risk in practice change.	Yes	Yes	Yes (no hysteresis)

Source notes: This list of papers is comprehensive, several papers which are closely related, or which derive their results from papers in this list are not referenced.

Appendix 2: Cumulative risk distribution of annual net profit – GBR grazing

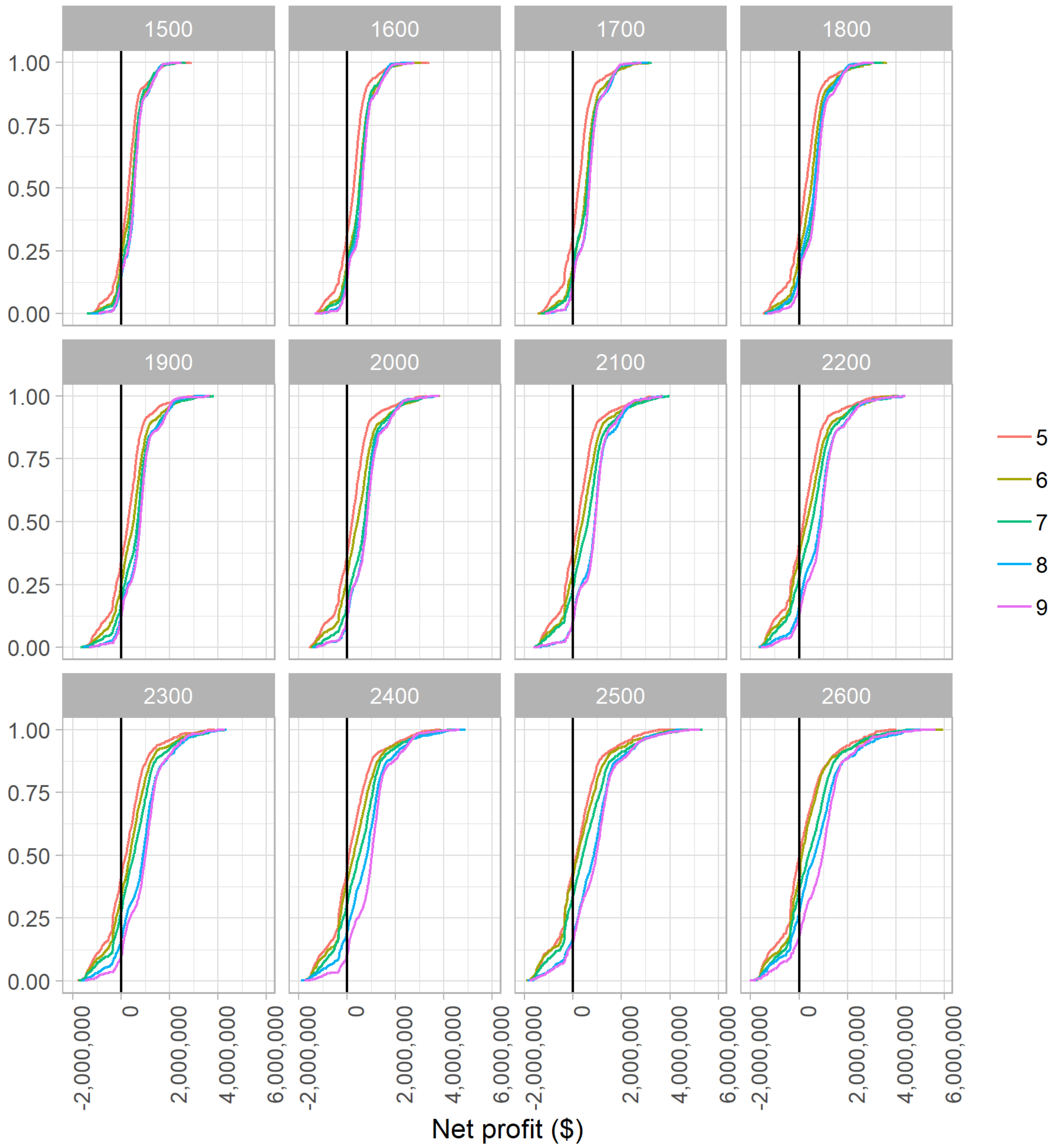

Figure 10: The cumulative frequency distribution of annual net profit ($) for each maximum number of breeders kept (graphs) and initial land condition (lines) for the 20 iterations of 50 year simulations given destocking of steers, weaners, wet and dry breeders

Appendix 3: Profit measures for grassy woodlands under climate change

Table 9: Boorowa annual farm net profit from different pasture states

Summary statistic	Farm net profit before farmer's salary and tax ($ $farm^{-1}$ yr^{-1})							
	Chromosol				Sodosol			
	fnative	hnative	dnative	onative	fnative	hnative	dnative	onative
Minimum	(194,269)	(357,124)	(322,200)	(230,682)	(245,712)	(283,684)	(316,115)	(219,263)
Maximum	337,328	233,767	176,841	127,698	250,087	142,047	318025	86,716
Average	109,452	3,492	16,838	(15,335)	74,154	(21,573)	(5,878)	(28,810)
Median	110,382	9,842	26,155	(15,940)	77,545	(14,686)	1,218	(24,529)
Standard deviation	87,866	74,852	74,180	56,337	72,612	65,378	84,850	49,291
Standard error	7,923	6,749	6,689	5,080	6,547	5,895	7,651	4,444

Notes: Measures of the annual farm net profit before farmer's salary and tax and its variability on the fertilised ('fnative'), healthy ('hnative'), degraded ('dnative') and overgrazed ('onative') native pasture states on the Chromosol and Sodosol soils. Results represent values simulated for 40-year periods based on projected future climates predicted from four different GCM models.