Asymmetric Ecological and Economic Responses for Rangeland Restoration: A Case Study of Tree Thickening in Queensland, Australia

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On the Ground

- Ecological and economic thresholds are important considerations when making decisions about safeguarding or restoring degraded rangelands.
- When degradation levels have passed a threshold, most managers figure it is either time to take action or too late to take action depending on the particular circumstances of the case.
- Considerations of ecological responses and thresholds have largely come from rangeland studies involving perennial vegetation with long-lived cycles of causes and effects, whereas thinking on economic responses to management and thresholds have often been informed by studies of weeds and pests in annual pastures and crops where cycles are fairly short and responses to control are generally fast.
- In many cases of rangeland degradation, an asymmetry may exist between opportunities for taking action on the basis of shorter-term ecological signals and where that action will actually yield an economic response, which is often in the intermediate to longer term.
- In many cases the time for economically warranted action is well past the point at which low-cost ecological control options exist, leaving only scope for higher-cost treatments or capitulation.

Keywords: ecological thresholds, economic thresholds, rangeland rehabilitation, prescribed fire, timber thickening, ranching, bio-economic modelling.

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Ecological and economic responses and "thresholds" have considerable relevance to sound rangeland management and monitoring, particularly for preventing soil and vegetation degradation or restoring lost productivity once damage has occurred. Both kinds of thresholds relate to points at which some kind of management intervention is either warranted or might no longer be worthwhile, and this is particularly pertinent to the context of brush or timber management. Ecological thresholds reveal deficiencies in land resource management and are well illustrated by state-and-transition models that describe shifts in range condition states with increasing gradients of management pressure or disturbance.[1] Economic thresholds typically involve the interplay of diminishing benefits and increasing costs and draw heavily on the weed and pests management literature for agricultural crops.[2]

When we are working with rangeland resource degradation or rehabilitation issues, the life cycles of perennial plants, times to impact, and feedback from management interventions are usually much longer than the short-term impact and feedback to treatment cycles of weed and pest outbreaks in annual pastures and crops. In this context an asymmetry may exist between appropriate responses for management action on the basis of ecological signals and where that action might yield an immediate economic response. Due to delayed feedbacks in production responses to resource impairment, the case for economically warranted action may be signaled well past the point at which lower-cost ecological management options might exist, leaving scope only for higher-cost interventions or even capitulation.[3] The environmental and economic context and ecological processes are important for addressing such management opportunity asymmetries. At low levels of apparent harm, the ecological response to treatment may be of limited economic value relative to the immediate cost of taking action. Where the level of resource impairment is already severe there may be a positive, but limited, ecological response to treatment, but it may not be sufficient to overcome high remedial costs with limited economic gain. In fact, an intermediate position involving a higher ecological response and a less substantial intervention cost may yield the highest economic gain.

It is particularly challenging to use simple field experiments to demonstrate the existence and nature of asymmetries in ecological and economic responses to range restoration opportunities. This is because of the complex and systemic nature of most rangeland degradation and recovery processes and the specific bio-physical context in which they occur. However, with advances that have occurred in simulation modelling of rangeland vegetation responses to climate and management it is possible to explore the interplay between such processes and contexts. In the rest of this article we consider ecological and economic response thresholds and asymmetry concepts and then use simulation modelling to explore some implications for management in the context of timber regrowth challenges facing a hypothetical beef ranching enterprise in Queensland, Australia.

Responses and Thresholds

Ecological Thresholds

Ecological thresholds have been widely canvassed in the range ecology and management literature.[4] These thresholds identify management pressure points beyond which rangeland pastures undergo a transition between "more productive" and "less productive" ecological states, as might be classified by vegetation or soil resource conditions.[5] The nonlinear ecological response and threshold concept is schematically presented for a subtropical woodland pasture in northern Australia in Figure 1. As grazing pressure increases with time, and is periodically exacerbated by drought, the pasture shifts from a highly productive state dominated by "desirable" perennial grasses and few woody trees and shrubs through various intermediate states, until an ultimate low productivity state is reached that is dominated by sparse annual herbage, bare ground, and a dense shrub or tree layer.[6] The transition paths are essentially asymmetric and the dashed "M–M" line identifies a point (another form of threshold) beyond which reverse transitions will require significant management intervention, such as chemical or mechanical treatments rather than lower-cost ecological options such as resting from grazing and prescribed fire. Despite their apparent simplicity, some important considerations for management that can be drawn from such models are the transient nature of the states, uncertain triggers and transitions, asymmetric pathways, the temporal scale of the transitions, and the possibility of employing different management options to achieve rehabilitation objectives.

Economic Thresholds

Economic thresholds represent points beyond which management action becomes warranted to limit some damaging process (e.g., weed ingress into pastures). The concept is generally built around the notion of a functional relationship between the density of the damaging agent (e.g., weeds), the intensity of control (e.g., spray applications), and economic yield (e.g., livestock or crop produce).[2] If this relationship can be identified then the benefits and cost of control can be estimated for various damage and yield response levels, and a threshold identified beyond which the cost of undertaking additional levels of control exceeds the additional benefit to be gained. This concept is illustrated schematically in Figure 2 for a weed-induced damage problem in a short-lived pasture or crop. When control is undertaken at low weed densities, the marginal (incremental) cost of treatment is likely to be low and the marginal (incremental) benefit in terms of avoided yield losses is likely to be high, whereas the marginal cost of employing control measures when weed densities are high is likely to be high and the marginal benefits will be relatively low. An economic optimum or threshold will be located

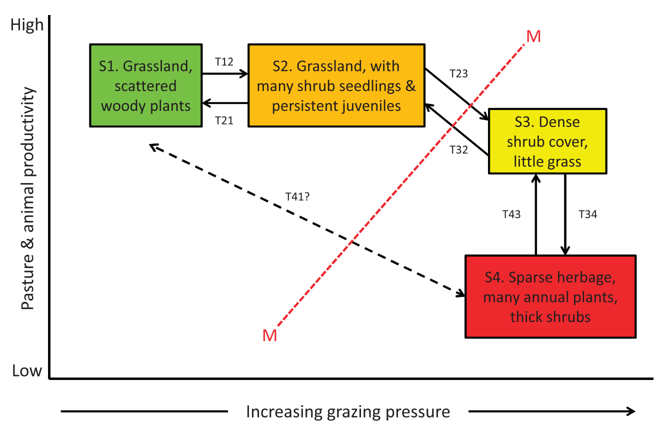

Figure 1. Ecological thresholds schematically illustrated with vegetation condition shifting between multiple states within a state-and-transition model (after Westoby et al.[1]). M–M indicates a notional threshold beyond which transitions to more productive states can only be accomplished by significant management interventions.

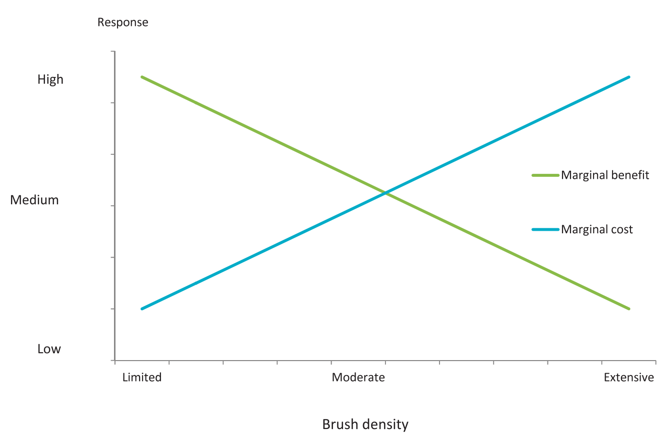

Figure 2. Economic thresholds schematically illustrated with declining marginal benefits and increasing marginal costs over an increasing gradient of brush density (after Auld et al.[2]).

at an intermediate weed density where the marginal costs and benefits of taking action are similar.

Asymmetric Ecological–Economic Management Responses

Figure 2 illustrates the economic threshold concept in simple terms, but its logic is better suited to the annual production cycles and short yield–control feedback loops of seasonally grown pastures and crops. This is generally atypical of the context of perennial range pastures and livestock production cycles, where the impacts of management and the environment on yield responses are typically long-lived.[3] The trajectories of brush densities and consequent responses in animal production that define the relevant benefit and cost relationships for brush or timber encroachment and control scenarios are more likely to follow the schematic pattern that is illustrated in Figure 3. For example, woody shrub encroachment and timber thickening in northern Australian rangelands is generally triggered by episodic climatic events, such as above average summer rainfall allowing juvenile plants to recruit into pastures that have been previously weakened by drought or poor grazing and fire management.[7] At that point (around year 2 as illustrated) various lower-cost ecological options such as prescribed fire, strategic resting, or targeted grazing might be successfully employed to curb the recruitment of new plants. Without this early intervention, the shrub population density increases over time and the scope to employ effective ecological options diminishes and the need to resort to more expensive management options (e.g., chemical or mechanical thinning) increases—in effect, crossing the M–M management intervention threshold of Figure 1. The competitive relationship between increasing shrub and tree densities and pasture yield is usually nonlinear with limited suppression of herbage yield at low to medium levels of shrub encroachment or tree thickening.[7] Compounded by selective grazing behavior, the impact of increasing brush and tree density on livestock production is also typically nonlinear as animal yields and economic returns decline with time and proportionally higher levels of brush and tree densities. The immediate benefits of implementing some control are generally limited at low density levels and only become apparent through animal yields at relatively high densities. By that point the treatment effectiveness of cheaper ecological options has been largely eliminated and the cost-effectiveness of applying more intensive treatments is severely challenged, if not also eliminated. In this sense, there is a sizeable temporal gap between the ecological and economic opportunities for taking effective management action. Note that the stylized shrub density and animal productivity response curves in Figure 3 are depicted on separate vertical axes and the intersection point is not intended to represent an optimum point in the same sense as the intersecting marginal benefit and cost lines that were depicted in Figure 2.

We now place this concept of asymmetric management opportunity in a more practical setting using a simple case study that employs computer simulation modelling of a typical beef ranching enterprise located in the subtropical woodlands of Central Queensland, Australia. The ranch is confronted with a problem of declining pasture productivity in many of its paddocks due to regrowth of previously cleared tree stands. The background to the simulation modelling approach that we have employed and some basic detail on the case study ranch are provided in the following section. The results are presented in the section after that.

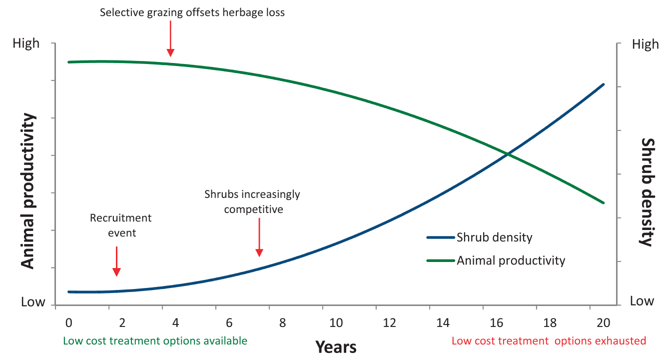

Figure 3. Shrub density and animal response trajectories schematically illustrated for a hypothetical shrub encroachment scenario.

Simulation Case Study

Meat and Livestock Australia commissioned the Northern Grazing Systems project in 2009 to explore best-practice range management strategies for nine agro-ecological regions spanning northern Australia.[8] Representative beef ranching enterprises were defined for each region and their production and economic performance was assessed for the various management practices using multiple-year simulations of a linked range pasture production model (GRASP) and a beef herd economic model (ENTERPRISE).[8] We use the ranching enterprise that was developed for the Central Queensland agro-ecological region to explore the asymmetric ecological–economic response concept for a prescribed fire intervention that is employed to address a timber regrowth problem.

Central Queensland Case Study

The GRASP–ENTERPRISE model was calibrated for a cow–calf breeding enterprise that is located at Duaringa in the Fitzroy River region of Central Queensland (lat 23043′S, long 149040′E, 94 m above mean sea level, mean rainfall 1980–2010 approximately 609 mm). The 10,500-ha ranch carries a mixed-age Brahman breeding herd of approximately 1,550 adult equivalents (1 adult equivalent = 450-kg non-pregnant, nonlactating breeding cow) and turns off heavy steers from grass pasture for the premium Japan Ox export market (target turnoff age and weight are approximately 2.5–3 years old and approximately 590–620 kg/steer live weight); otherwise the steers are sold into lighter export categories (e.g., 2.0–3.0 years old and approximately 520–580 kg/steer live weight). The ranch has 15 breeder paddocks comprised of native and sown pastures with ongoing timber regrowth problems, which if left untreated will impair the longer-term pasture and herd productivity. The timber regrowth treatment employs a prescribed fire regime that is applied in a one-in-four-year rotational sequence (25% of area treated annually) subject to the availability of sufficient herbage fuel loads to successfully carry a fire, and the maximum effectiveness of a single burn is 30% mortality of the targeted trees. Because the context in which the pasture degradation problem is occurring is particularly important, the simulations are conducted for a range of starting pasture condition states of differential tree basal areas (0.5 m^2/ha to 5.0 m^2/ha) and timber thickening rates under grazing (annual rates ranging from 1% to 25%). The condition of the soils and vegetation in the affected paddocks varies from B, or good, to C, poor and degraded, as rated against a four-category ABCD land-condition rating system that is commonly used in northern Australia to assess rangeland resource condition and trends.[9] The GRASP pasture yield simulations are applied using Duaringa climate records for 1890–2010. Livestock prices used in the ENTERPRISE model are the mean values quoted for the relevant classes of finished stock in 2013 (Meat and Livestock Australia—National Livestock Report). Husbandry and marketing costs are derived from agribusiness operations in the Duaringa region for 2013. Ranch overhead cost and capital structures are the median estimates derived for ranches in the region.[10] These economic parameter values are held constant across each year of the simulations and are summarized in Table 1.

Table 1. Key economic parameter values used in the ENTERPRISE model, Duaringa case study

Parameter	Unit value \$ Australian*
Sale price steers, export ox (Japan)	$1.75/kg live weight
Sale price steers, light steer (Korea)	$1.65/kg live weight
Sale price heifers, manufacturing grade (United States)	$1.40/kg live weight
Sale price cows, manufacturing grade (United States)	$1.10/kg live weight
Purchase price, bulls (average)	$4,500 per head
Cartage on sale animals, steers	$11.00 per head
Cartage on sale animals, heifers/cows	$10.00 per head
Husbandry costs, steers	$9.80 per head
Husbandry costs, heifers/cows	$9.61 per head
Husbandry costs, calves	$6.80 per head
Husbandry costs, bulls	$9.00 per head
Marketing charges	$5.50 per head
Bull/cow ratio	4%
Weaning weight, steers	230 kg
Culling weight, cows	540 kg
Culling weight, heifers	340 kg

*$1.00 Australian ≅ $0.91 United States (valued on 12 December 2013).

Simulation Model

Pasture parameter values and soil types relevant to the Duaringa region and the assumed condition of the 15 paddocks were input into GRASP to estimate pasture yield, annual carrying capacity, and animal live-weight gain for both the "nil treatment" and the "with-fire treatment" scenarios. GRASP is a dynamic, deterministic, point-based model that simulates soil moisture, pasture growth, and animal production from daily inputs of rainfall, temperature, humidity, pan evaporation, and solar radiation. The effect of land condition is assessed using a combination of the percentage of perennial grasses in the pasture sward with consequent changes in several pasture growth parameters. Relationships between the understory species and overstory species are characterized by competition for available water and nitrogen.[11] The annual live-weight gain of animals is simulated as a function of forage utilization and growing season length.[12] The simulated steer live-weight gain and stocking rate for each paddock from GRASP is input to the ENTERPRISE herd economic model. Herd reproduction and mortality rates that underpin the herd structure through time are linked to the animal growth projections using regression equations based on long-term herd performance records from Swans Lagoon Research Station and climate data for Duaringa. ENTERPRISE projects the total animal numbers by sex and age class and animal turnoff rates, and generates an array of profit measures (e.g., beef gross margins, net profit, etc.) for each year of a simulation trial.

Results

We now present some physical results from the GRASP pasture simulation trials in the following subsection and then the ENTERPRISE herd economic simulations in the subsection after that.

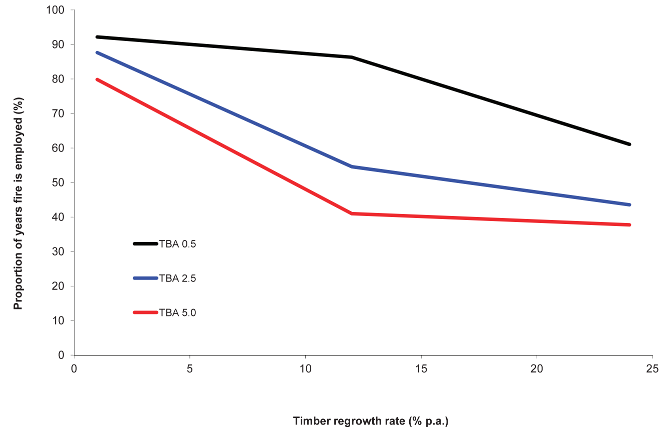

Figure 4. Relationship between starting tree basal area (0.5 m^2/ha, 2.5 m^2/ha, and 5.0 m^2/ha), projected percentage of annual regrowth rate of timber, and proportion of simulation years in which a sufficient fuel load is present for a successful prescribed fire intervention.

Pasture Simulations

Burn capacity frequency. Although the prescribed fire scenario is nominally set as a planned routine of one-in-four-year fire cycles, the ability of the pastures to actually carry a fire in given year depends on both the starting timber density and the simulated growth rate of the timber stands, including additional recruitment, and also on the grazing pressure that is applied. From Figure 4 it is evident that the capacity to carry a fire in any year (frequency of fuel load sufficiency) decreases as the starting timber density (TBA) and annual tree growth rates (%) increase.

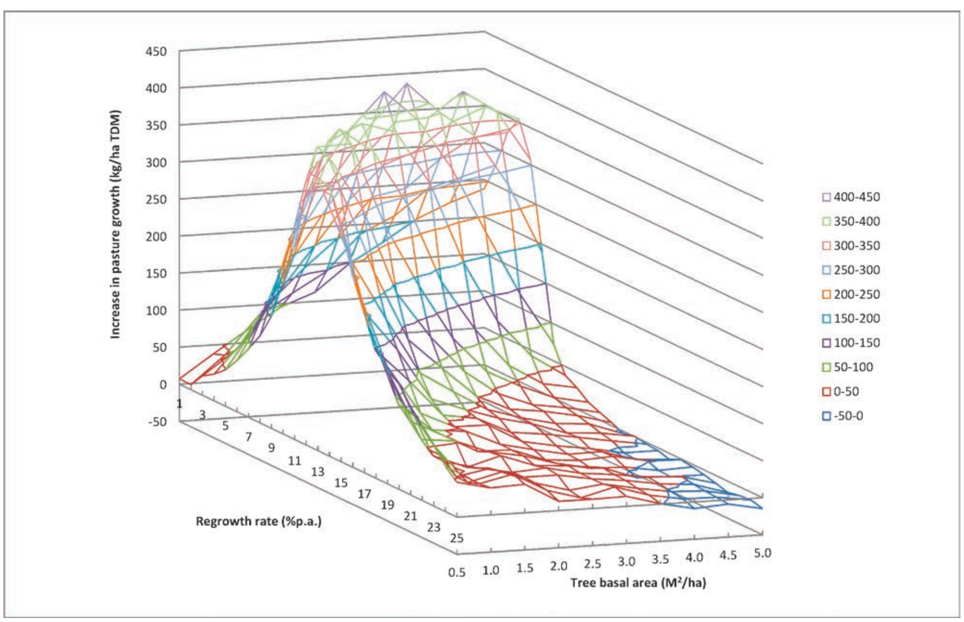

Figure 5. Relationship between starting tree basal area (0.5 m^2/ha to 5.0 m^2/ha), projected percentage of annual regrowth rate of timber, and projected annual increase in pasture herbage growth. TDM indicates total dry matter (kg/ha).

Pasture growth difference. The relative advantage of undertaking a prescribed fire program for pasture rehabilitation is also partly determined by the initial density and regrowth rate of the targeted timber species as shown in Figure 5. For a given initial tree density, the simulated net response in herbage yield to treatment over the nil treatment rate initially increases with increasing rates of regrowth and then declines. Low to moderate timber regrowth rates reduce the scope for differences between nil treatment and with-fire treatment herbage yields, whereas high rates of timber regrowth generally suppress the scope for generating sufficient fuel to maintain effective fire cycles (Figure 4). The latter effect comes increasingly into play at lower timber regrowth rates with increasing initial timber densities. The largest overall response of herbage yield occurs at intermediate initial timber densities through the interplay between the fire frequency opportunity and the suppression of potential timber regrowth.

Steer growth advantage. Animal growth is generally dependent on the availability and quality of herbage that is on offer. The production advantage of the prescribed fire treatments as represented (for example) by the simulated mean difference in annual live-weight gain of steers above the nil treatment rate (Figure 6) necessarily follows a similar pattern to that of the simulated herbage response (Figure 5). Herd fertility and mortality rates also determine the herd productivity and the projected responses (not shown) follow a similar pattern due to the regression linkage to animal growth rates.

Herd Economic Simulation

The ENTERPRISE model generates an array of profitability measures for the ranch enterprise for a given simulation run. As this case study is considering the impact of prescribed fire for timber regrowth control, estimates of economic advantages are presented as the discounted net present value (NPV) of the difference of simulated streams of annual net profit per hectare between the nil treatment and with-fire treatment scenarios. A discount rate of 5% is used for the NPV calculations. The economic results are summarized in Table 2 for three starting timber densities (TBA 0.5 m^2/ha, 2.5 m^2/ha, and 5.0 m^2/ha) and three annual timber regrowth rates (1% per year, 12% per year, and 24% per year).

Foremost, it is apparent that the case study ranch would not be economically viable if both the initial standing timber density and projected regrowth rates are either intermediate or high (TBA 2.5 m^2/ha, 5.0 m^2/ha; regrowth 12% per year, 24% per year). For those combinations the productivity of both the pastures and animals is so low that neither the baseline nor the prescribed fire scenarios generate positive income streams (i.e., cover the ranch overhead costs). Unfortunately, this is the very situation that many Australian ranches with acute shrub and timber problems actually find themselves in with little scope to retrieve their viability and persist. For the remaining combinations of starting timber density and regrowth rates, the projected economic returns are necessarily consistent with the simulated timber regrowth treatment effects and herbage responses. If the timber density at the start of the simulation is relatively low (0.5 m^2/ha), then the largest economic return from timber treatment will occur at intermediate timber regrowth rates (12% per year). For this starting timber density state, when timber regrowth rates are low (1% per year) herbage productivity is already high and any further increase in animal production following treatment is not sufficient to cover both the direct cost of managing the fire regime and the lost grazing opportunity on 25% of the

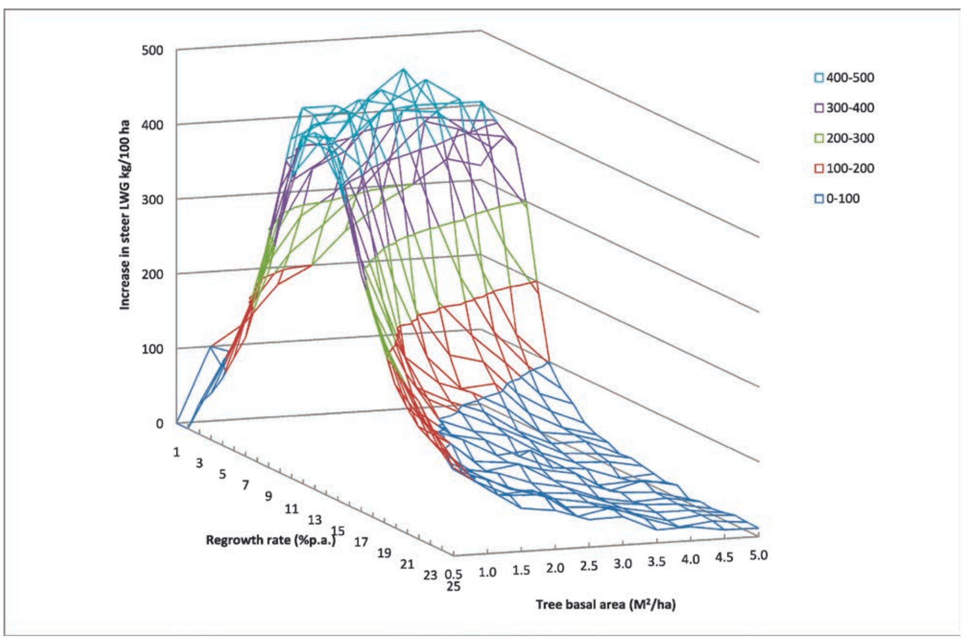

Figure 6. Relationship between starting tree basal area (0.5 m^2/ha to 5.0 m^2/ha), projected percentage of annual regrowth rate of timber, and projected annual increase in steer live-weight gain (kg/100 ha).

Table 2. ENTERPRISE model results: projected net present value of net economic profit/ha (5% discount rate) for burn and no-burn scenarios under three starting tree basal areas (0.5 m2/ha, 2.5 m2/ha, and 5.0 m2/ha) and three annual tree regrowth rates (1%, 12% and 24% per year). Simulation period, 1890–2010 (Duaringa)

Initial tree basal area	Net profit (mean of simulation)	Timber regrowth rate		
		1% per year	12% per year	24% per year
0.5 m^2/ha	Prescribed fire	$645.88	$478.53	$28.66
	Nil fire	$713.28	$305.08	–$10.22
	Difference	–$67.40	$173.45	$38.83
2.5 m^2/ha	Prescribed fire	$441.76	–$59.68	–$152.44
	Nil fire	$371.95	–$90.67	–$164.67
	Difference	$69.81	$30.99	$12.24
5.0 m^2/ha	Prescribed fire	$181.34	–$173.89	–$193.51
	Nil fire	$76.02	–$181.62	–$196.49
	Difference	$105.33	$7.73	$2.98

total paddock area that is burnt. At the highest timber regrowth rate (24% per year) the herbage productivity is low for both the with-fire treatment and the nil treatment scenarios with little gain in profit from remediation management. This is primarily due to the prescribed fire regime being episodically disrupted by insufficient fuel to either initiate or support an effective burn. As noted, when the initial timber density is intermediate to high the prescribed fire regime is only economically effective when the annual timber regrowth rate is low. In effect, as the starting timber densities increase, usually as a legacy of poor previous management, the gap between the ecological and economic opportunities widens with lower annual regrowth rates because the relative production gain from imposing a fire treatment increases with the initial timber density. At increasingly higher annual rates of timber regrowth, for a given starting timber density, the economic gains from undertaking treatment fall away and the gap between the two thresholds is thereby compressed.

Conclusions

We now draw some conclusions from this simple case study. Foremost, for the Duaringa example at least, the results suggest that a prescribed fire strategy for timber regrowth control can be profitable, as has previously been suggested by some relatively simple partial budgeting studies.[13] However, the magnitude of the economic response is an interplay of several contextual factors including the starting tree basal area, the timber regrowth rate, the fire regime and the effectiveness of a given burn (both fixed in this case study), and the availability of sufficient fuel to carry a successful fire.

At low starting timber densities there is a higher frequency of burning opportunities, but also limited economic advantage to be gained from applying fire at both high and low timber regrowth rates. The ecological effectiveness of the burning regime diminishes with higher starting timber densities and moderate to high timber regrowth rates, combinations that are also not economic to treat. Of note, the combination of a low starting timber density and low regrowth rates is also not economic to treat, whereas the ecological effectiveness of imposing a prescribed fire treatment is also at a peak under those very same circumstances. The economic and ecological advantages of imposing a fire management regime more closely align under moderate to poor starting conditions and low timber regrowth rates.

This particular study is just one of many range restoration cases that could be explored using a simulation modelling approach, such as that employed for the Northern Grazing Systems project. Even here there is considerable scope for conducting a more wide-ranging study including, for example, such considerations as varying the climate regime (e.g., to account for different scenarios of future climate change) and changing fire regimes and the effectiveness of a given burn. Nevertheless, our aim was to consider the potential discrepancy between ecological and economic responses to rangeland rehabilitation options and to consider some of the contextual factors that may bear on the nature and magnitude of the differences.

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