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LINKING LAND AND WATER MANAGEMENT TO RESOURCE CONDITION TARGETS

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An adaptive approach to vegetation and biodiversity management in the Goulburn Broken catchment

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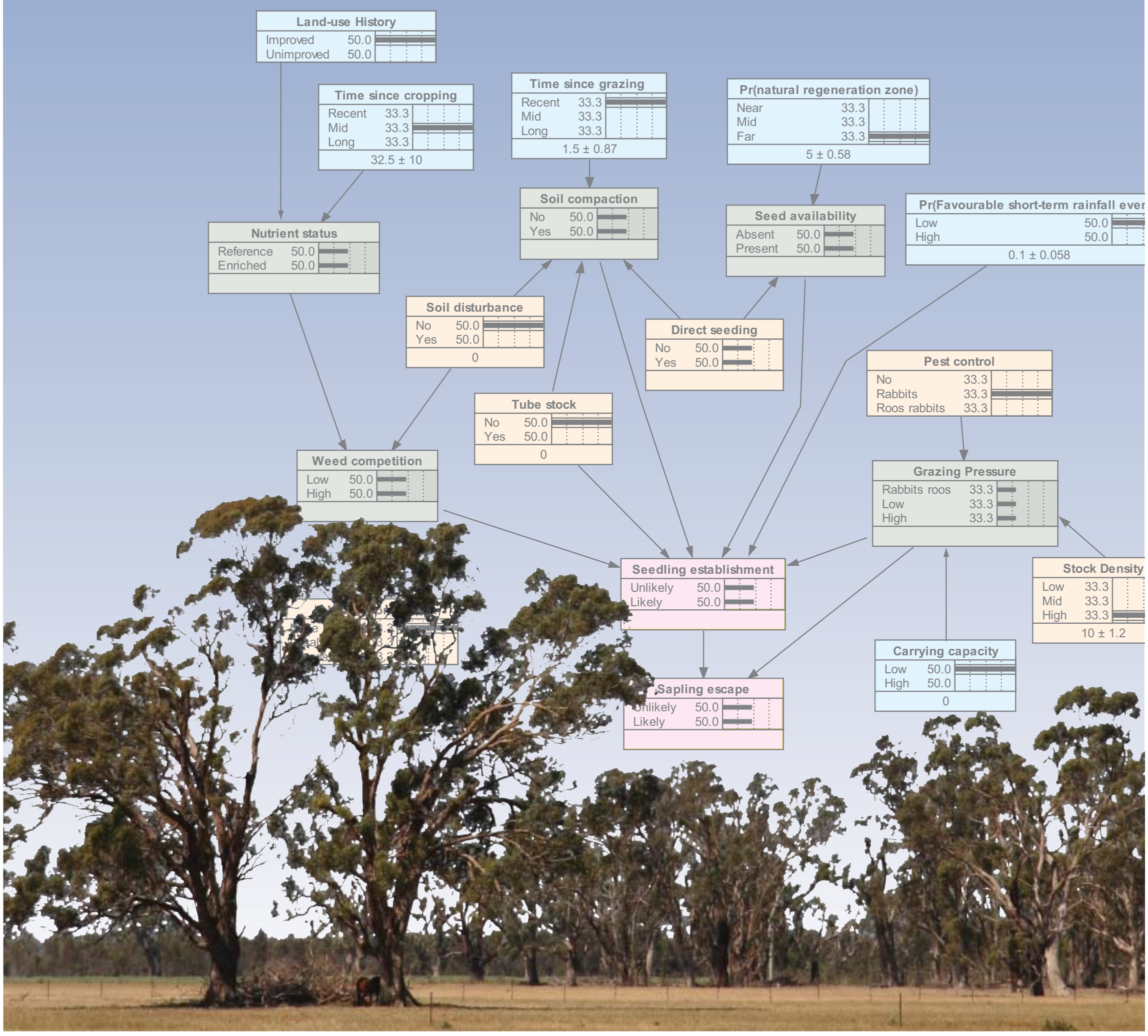

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Cover photo: Remnant Grey Box woodland on private property near Longwood (Photo: Garreth Kyle)

LANDSCAPE LOGIC is a research hub under the Commonwealth Environmental Research Facilities scheme, managed by the Department of Environment, Water Heritage and the Arts. It is a partnership between:

- **six regional organisations** – the North Central, North East & Goulburn–Broken Catchment Management Authorities in Victoria and the North, South and Cradle Coast Natural Resource Management organisations in Tasmania;
- **five research institutions** – University of Tasmania, Australian National University, RMIT University, Charles Sturt University and CSIRO; and
- **state land management agencies in Tasmania and Victoria** – the Tasmanian Department of Primary Industries & Water, Forestry Tasmania and the Victorian Department of Sustainability & Environment.

The purpose of Landscape Logic is to work in partnership with regional natural resource managers to develop decision-making approaches that improve the effectiveness of environmental management.

Landscape Logic aims to:

1. Develop better ways to organise existing knowledge and assumptions about links between land and water management and environmental outcomes.
2. Improve our understanding of the links between land management and environmental outcomes through historical studies of private and public investment into water quality and native vegetation condition.

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An adaptive approach to vegetation and biodiversity management in the Goulburn Broken catchment

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Executive summary

The Goulburn Broken Catchment Management Authority (GBCMA) has a mission to conserve biodiversity across their jurisdiction. Amongst their peers GBCMA is acknowledged as a leading NRM agency. Nonetheless, the impact of their investment programs remains highly uncertain. There are several important reasons for this. First, there is uncertainty regarding how on-ground management helps achieve the various Resource Condition Targets for native vegetation management across the catchment. Second, the current standard for native vegetation data collection at investment sites is too insensitive to short-term change to support adaptive learning. Third, there is a lack of models that demonstrate linkages between vegetation condition variables and other biodiversity values, particularly fauna habitat, with which they are presumed to be correlated. Last, there is much uncertainty regarding how achieving the Resource Condition Targets translates to progress toward the biodiversity mission (of species persistence).

To address these limitations, GBCMA is considering an Adaptive Management (AM) framework to prioritise actions, monitor their efficacy, and to facilitate reporting to stakeholders. AM is a 'learning by doing' approach that acts to reduce uncertainty in management options by monitoring and feedback mechanisms. It ensures that future management decisions are socially and scientifically defensible by providing an explicit framework for motivating change, designing interventions and interpreting the results of monitoring. Commonly, there is a considerable gulf between rhetorical commitment to AM and its implementation. This report summarises the first developmental phase of a working example of adaptive management of native vegetation in the GBCMA. The report is presented in four parts. The first section provides an outline of the key elements of an AM framework. The second section is an illustration of how the first three steps in the AM framework may be applied, focusing on the development of a process model for seedling establishment within non-riparian woodlands. The third section deals with some of the sampling decisions that require consideration when designing a monitoring program around detecting change in the face of uncertainty. Last, we present examples of first-cut process models for vegetation quality and bird diversity.

We use Bayesian Belief Networks (BBNs) to structure the process models as they provide a method that is easily interpreted and intuitive. These models can be used to help design a more informed management and monitoring strategy for the GBCMA. In order to close the adaptive management loop the models need to be validated and updated with appropriate data and we illustrate some important data collection considerations. These include the identification of appropriate measures and environmental variables to add to a monitoring strategy, how we might use the model to identify which management interventions are required at a given site, and how we can use the subsequent data collected in a monitoring strategy to improve our confidence in the relationships and thresholds used in the models.

Contents

Introduction

Background

Large investments in native vegetation restoration are being carried out throughout Australia. However, there is little certainty about the nature and magnitude of environmental benefits arising from those investments (Freudenberger *et al*. 2004; Dorrough *et al*. 2008b; Duncan and Wintle 2008; Lefroy 2008; Vesk *et al*. 2008). There remains substantial uncertainty about which restoration strategies are most efficient in terms of benefits per dollar invested. This is not an uncommon feature of natural resource management, which is prone to uncertainty and unpredictability due to the highly complex nature of biological systems (Walters and Hilborn 1978); and may be carried out over large temporal and spatial scales (Ringold *et al*. 1996). There is an urgent need to learn about and demonstrate the environmental benefits arising from investment to ensure that actions are efficient and benefits are sufficient to justify substantial public outlay. This requires a monitoring strategy that is targeted to assess progress towards program objectives and evaluate the extent to which particular actions contribute to that progress (Duncan and Wintle 2008).

Adaptive Management (AM) is commonly advocated as a way to deal with some of these issues. AM is a 'learning by doing' approach that acts to reduce uncertainty in management options by monitoring. It ensures that future management decisions are socially and scientifically defensible by providing an explicit framework for motivating, designing and interpreting the results of monitoring (Ringold *et al*. 1996; Parma 1998; Yoccoz *et al*. 2001; Shea *et al*. 2002; Schreiber *et al*. 2004; Allan and Curtis 2005; Nichols and Williams 2006; Duncan and Wintle 2008). The benefits of the AM framework are widely appreciated and cited in scientific and management literature. However, to date there remains few successful examples of its implementation in natural resource management (Walters 1997; Lee 1999; Stankey *et al*. 2003; Allan and Curtis 2005). Somewhat perversely, some of the problems cited, such as complexity of natural systems and uncertainty about management effectiveness, are the very factors that make AM arguably the only approach likely to offer transparency and defensibility for management actions. Whilst we acknowledge that implementing AM is not simple, particularly in complex institutional settings such as catchment management authorities (CMAs) (e.g., Allan and Curtis 2005), we are convinced that it is both possible and necessary. This report provides justification, discussion and a preliminary model toward the development of a discrete working example of adaptive management of native vegetation, using the Goulburn Broken Catchment Management Authority (GBCMA) as a case study.

The logic behind an Adaptive Management approach for GBCMA)

GBCMA has a mission to strategically invest public money to encourage land management practices that conserve biodiversity across the catchment and currently specifies various management objectives (targets) that aim to achieve this mission (GBCMA 2003, 2007). These objectives (targets) are set at different spatial scales that are described in the Regional Catchment Strategy, ranging from 'outcome oriented' to site-scale 'output oriented' targets (GBCMA 2003, 2007). The overarching Biodiversity Mission is ''to protect and enhance ecological processes and genetic diversity to secure the future of native species of plants, animals and other organisms in the catchment'' (GBCMA 2003; 87). Underlying this are a series of shorter-term Resource Condition Targets (RCTs) specified for native vegetation.

GBCMA's investment towards its Biodiversity Mission occurs primarily via increasing native vegetation extent and quality (Figure 1). Unfortunately, models that convincingly link the management actions, outcomes and RCTs to the Biodiversity Mission are largely notional, despite decades of investment and considerable research. Thus, whilst ensuring that biodiversity is preserved across the catchment is an important long-term target, considerable research is required to determine how progress might be assessed. This is an important limitation beyond the scope of this report.

We focus on the level below the biodiversity mission, where there are assumptions made about how the management actions (output) are believed to translate into progress toward condition and extent RCTs (Figure 3; GBCMA 2007). These assumptions describe the expected trajectory of vegetation change in response to management. Progress toward achieving the Resource Condition Targets is reported using the following equation (GBCMA 2003, 2007):

> Outcomes (RCTs) = Outputs (on-ground achievements) x Assumptions.

These assumptions are based on empirical evidence, local knowledge, and best guess (GBCMA 2003). Uncertainty in progress toward the Resource Condition Targets is acknowledged as each assumption is assigned a 'certainty rating' (GBCMA 2007). In some cases, there remains substantial uncertainty around these assumptions and thus which management strategies are most efficient in terms of benefits per dollar invested. Such assumptions are common practice in natural resource management, particularly as reporting progress is made on short-time-frames. It is difficult to update these assumptions over time, and resolve uncertainty in progress towards the Resource Condition Targets, because there are few adequate performance measures with which to do so.

GBCMA recognises there is a need to learn about the effect of management on native vegetation to ensure that actions are efficient and benefits are sufficient to justify the level of investment. This requires a monitoring strategy targeted to assess progress towards program objectives and evaluate the extent to which particular actions contribute to that progress. GBCMA may consider adopting an adaptive management approach to more coherently prioritise actions, monitor their efficacy and to facilitate reporting to stakeholders.

Report outline

This report outlines the development of a working example of adaptive management of native vegetation in the GBCMA. The work is presented in four parts. Section 1 provides an outline of the four key elements of an AM framework: identifying objectives; management options; models of system response to management; and describing the method of allocating management effort across the suite of options using the management of native vegetation as an example.

In Section 2 we expand on the AM framework by developing a process model for seedling establishment within non-riparian woodlands. Section 3 explores the implications of sampling decisions that are required when designing a monitoring program for detecting change. Recruitment of seedlings is but one example of a performance measure relating to native vegetation management of importance to CMAs. Therefore, in Section 4, we present examples of first-cut process models for woodland bird habitat and a multi-objective example of vegetation structure and diversity improvement.

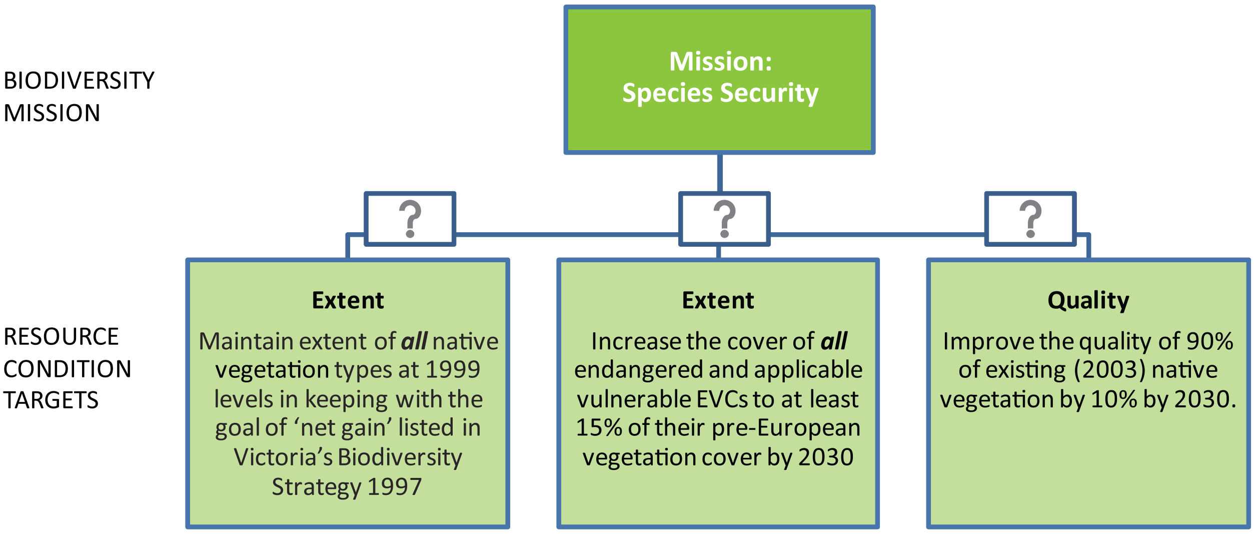


Figure 1. The GBCMA's long-term Biodiversity Mission and contributing Resource Condition Targets. The assumption here is that achieving the Resource Condition Targets will ensure the Mission is attained but this is highly uncertain.

The Adaptive Management framework

Uncertainty is an unavoidable feature of natural resource management because ecological processes and patterns are complex (Walters 1986). Adaptive Management (AM) is an approach that acknowledges management action must proceed in the face of uncertainty, and uses monitoring to iteratively update the state of knowledge and the subsequent direction of management (Walters 1986; Ringold *et al.* 1996).

AM involves learning about how a system responds to management through experience and acts to manage uncertainty in management scenarios through monitoring (Walters and Hilborn 1978; Walters 1986; Parma 1998; Shea *et al.* 2002; Schreiber *et al.* 2004; Nichols and Williams 2006; Duncan and Wintle 2008; Hauser and Possingham 2008). It provides the opportunity to continuously learn and update our understanding of the success of management options across space and time.

Using the AM framework, reporting at all levels provides meaningful (and tangible) outputs that can then be used to direct resources. Locally (on-ground), this refers to allocating funding according to which management option is best, and at a catchment management level this refers to identifying which areas of the catchment are responding constructively to investment.

Adaptive management monitoring design removes many of the (often onerous) statistical requirements that have undermined previous monitoring and research initiatives. Adaptive management allows for knowledge to accrue as management progresses; the more that is invested in targeted management 'experiments' and monitoring, the faster knowledge will accrue. However, there is no imperative to invest at any particular rate for fear of failing arbitrary statistical requirements. This is particularly appealing in the context of fluctuating funding (Duncan and Wintle 2008).

We describe the adaptive management strategy as having four key steps (Duncan and Wintle 2008), illustrated in Figure 2:

Step I: Identification of management goals, constraints and performance measures

Step II: Specification of management options

Step III: Identification of competing system models and model weights

Step IV: Allocation of resources, implementation of management actions and monitoring of management performance.

Step I. Measurable management goals, constraints and performance measures

The first step in adaptive management is to clearly define the management objectives (Nichols and Williams 2006; Duncan and Wintle 2008). These objectives require a clear spatial and temporal component, a specification of accepted uncertainty, explicit description of trade-offs and constraints, and defined measure(s) by which the management component can be assessed (Walters 1986; Nichols and Williams 2006; Duncan and Wintle 2008). These goals must also be expressed in ways that are suitable for measurement, and amenable to statistical inference and comparison. To be useful in an adaptive management framework, monitoring methodology needs performance measures, or response

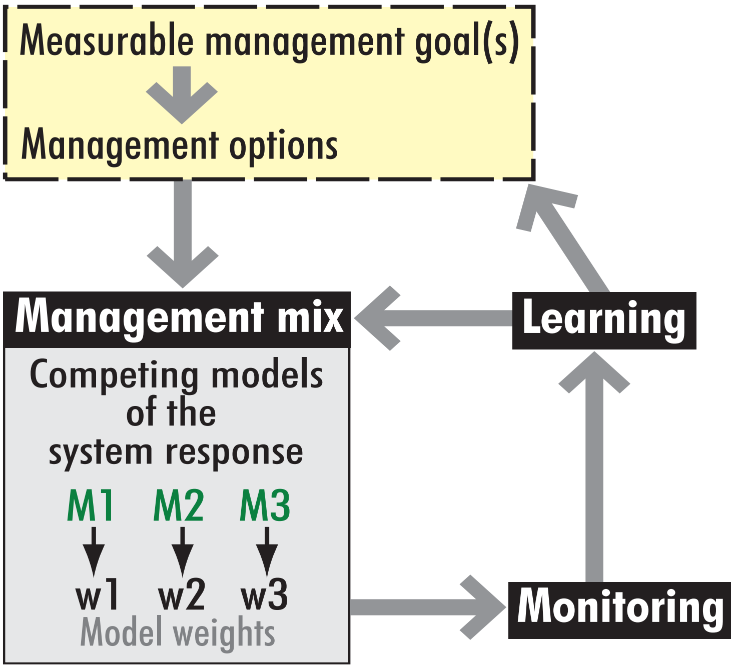


Figure 2. Steps in an adaptive management strategy. The dashed-line box indicates steps that require elicitation of social preferences, while the remainder of the process is largely the domain of technical experts (from Duncan and Wintle 2008).

variables that are directly relevant to the objectives and decisions at hand, and that are sensitive enough to detect 'important' changes over time (McCarthy and Possingham 2006; Duncan and Wintle 2008). Hence the questions of what should be measured are crucial.

The GBCMA already specify a number of management objectives for biodiversity conservation, as outlined by the Resource Condition Targets. However, achieving these targets requires a series of finer-scale management targets for which we can specify uncertainty, trade-offs and, most importantly, useful performance measures. Currently, we can consider that finer-scale, output-oriented management vegetation targets are implicit within the Resource Condition Targets but not specified. For example, the broader target (RCT) may be to increase the extent of all threatened and endangered EVCs within the catchment, whilst the finer targets underlying this refer to specific EVCs within the various bio-regions (see Figure 3). These are targets that require elicitation. In Section 3 we outline an example of a particular management objective that deals with the vegetation extent RCT.

Step II. Specification of management options

As with management objectives, management options are specified by the key stakeholders and managers (Nichols and Williams 2006; Duncan and Wintle 2008). Examples of management strategies supported by the GBCMA include remnant protection, revegetation of cleared sites, conservation covenants and strategies to promote regeneration of degraded sites (e.g. Bush Returns; Miles 2008). Within these strategies, management options may be broken down into more specific classes of actions. For example, levels of remnant protection may be achieved by any combination of fencing, stock reduction, cessation of firewood collection, and/or weed control.

The AM framework requires the specification of a number of plausible management options. These should represent the range of opinion and belief about what management might achieve the objective where the outcomes of these different options are uncertain. The investment in management options may be weighted according to prior knowledge and predictions of how well these options will

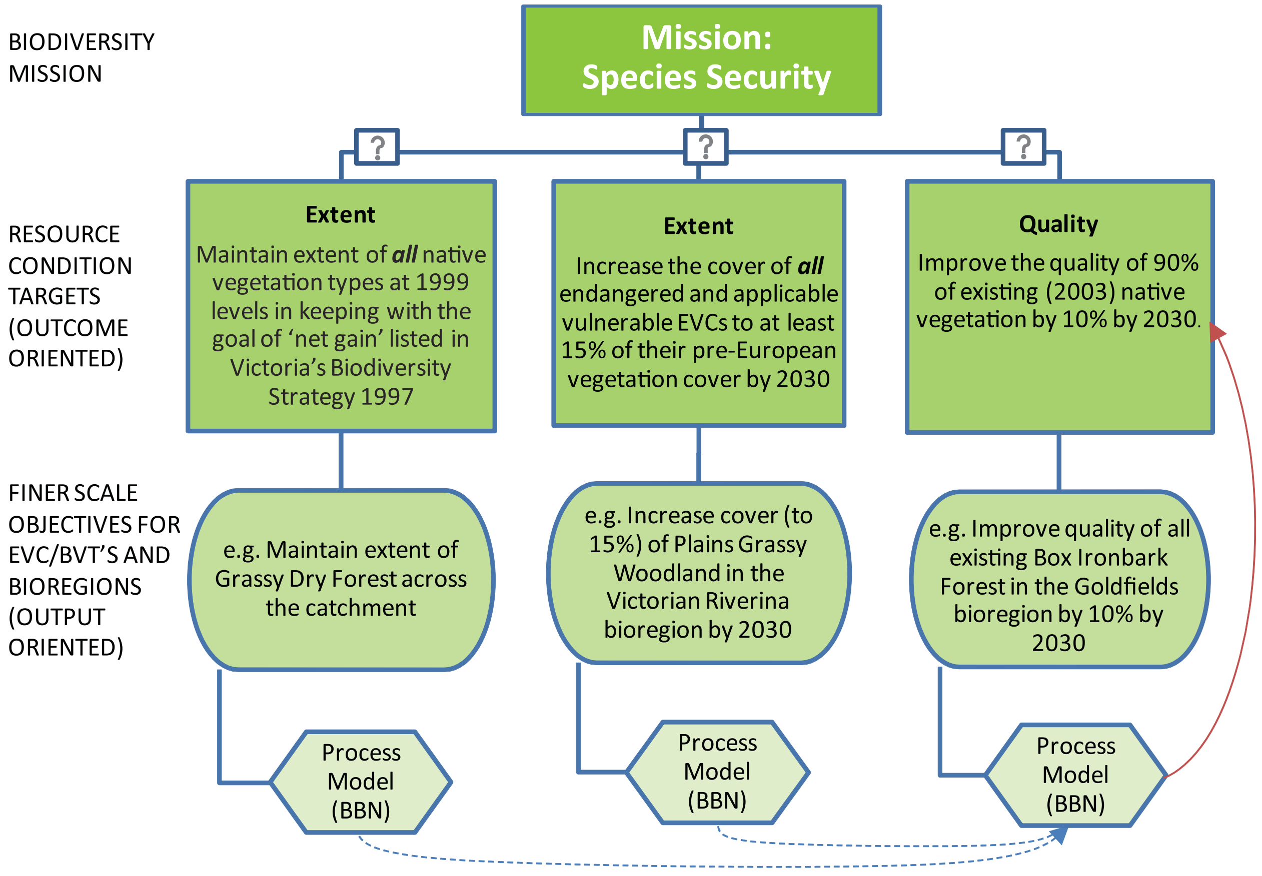


Figure 3. The relationship between the broad-scale, outcome-oriented management targets (Biodiversity Mission and Resource Condition Targets) and finer-scale, output-oriented management targets which are modelled using Bayesian Belief Networks (BBNs).

work in various systems over different time-frames. However, if little knowledge exists, or extreme uncertainty surrounds these options, then equal weighting (i.e. investment) is given. In the case where there is agreement regarding the management options that should be applied, learning can still occur by varying the level to which the management scenario is applied at a site. In Section 3 we outline some of the common management options used by the GBCMA to achieve an increase in the extent of native vegetation.

Step III. Identification of a system restoration response model(s)

The next step is to develop a series of process models that link potential vegetation management actions to explicit vegetation management objectives. The aim is to model how the (eco)system responds to different management actions and thus illustrate or forecast the most efficient management option to maximise the probability of restoration success.

Models may be based on expert opinion, best guess, and/or empirical studies. Uncertainty in identifying the best model is unavoidable as opinions regarding system dynamics will vary according to knowledge and experience. As a result, there may be a number of plausible hypotheses to explain system restoration responses, and more than one model may be needed to reflect model uncertainty. These models (or hypotheses) might indicate the application of different management strategies (Duncan and Wintle 2008; Hauser and Possingham 2008). Within AM, the knowledge and beliefs represented within the model are updated with data. Data accumulation occurs through monitoring key predictor variables and this data is used to update the relationships within the model.

The following section (3) illustrates the full development of a process model, and outlines how system models may be developed to inform the efficacy of management actions in meeting vegetation extent and quality targets (RCTs).

Step IV. Allocation of resources, implementation of management actions and monitoring of management performance

Allocating resources to the competing management options can be achieved using formal optimisation techniques based on the system models (refer to Hauser *et al.* 2006; McCarthy and Possingham 2006; Hauser and Possingham 2008). Alternatively, this may be determined by the GBCMA based on prior knowledge and expert opinion. Monitoring is then used to assess and evaluate the performance of management actions. Within an AM framework, evaluation occurs as a formal link to provide feedback in relation to the initial management objectives and performance measures. Without this link, monitoring alone is simply not a worthwhile exercise (Nichols and Williams 2006; Duncan and Wintle 2008).

Within AM, there is an explicit value placed on the learning (monitoring) component, which reflects a balance between the current state of knowledge regarding the efficacy of management actions and current management requirements (Walters 1986; McCarthy and Possingham 2006). One of the difficulties in the application of AM is that there is often a long lag time between observation (monitoring) and the implementation of the management action. This can make allocating resources between monitoring and management difficult. However, the value of learning can be expressed in terms of the expected benefit to the management objective (Walters 1986; McCarthy and Possingham 2006) which can be updated over time. This part of the AM framework is not dealt with in great detail within this report but some further discussion is provided in Sections 3 and 4.

Development of a process model

Rationale

Within the Goulburn Broken Catchment Management Authority's (GBCMA) Regional Catchment Strategy, there are a number of Resource Condition Targets (RCTs) specified for the management of native vegetation, two which refer to maintaining or increasing the extent/cover of applicable Ecological Vegetation Classes (EVCs, GBCMA 2003). Recruitment and cover of canopy species are commonly used as performance measures to monitor progress toward such targets. However, there remains considerable uncertainty around which environmental factors influence seedling establishment and to what degree (Vesk and Dorrough 2006). There is also considerable uncertainty about which management interventions should be used across the catchment to best achieve improvements in extent/cover. Resolving this uncertainty requires the development of a process model(s) that represents the relationships between system state variables, management interventions and the performance measure of interest (i.e. seedling establishment). That is, models of how we think the ecological system works and how it responds to management intervention. Monitoring is then used to assess and evaluate the performance of management actions and update the relationships within the process model.

In this report, we describe development of a model of seedling establishment within non-riparian woodlands within the Goulburn Broken catchment. We use Bayesian Belief Networks (hereafter BBNs) to structure the process models as they provide a method that is easily interpreted and intuitive (McCann *et al.* 2006). BBNs are graphical models of the relationships, or causal links, between a series of predictor and response variables (Marcot *et al.* 2001; McCann *et al.* 2006), and the strength of the links between variables is expressed in terms of conditional probabilities (Jensen and Nielson 2007). BBNs are used to model the influence of different management actions on key predictor variables and thus illustrate the management options that maximise the probability of restoration success under scenarios where land-use history or climatic conditions may vary (McCann *et al.* 2006).

The Bayesian Network Diagram

We first describe a Bayesian network diagram (Cain 2001) which graphically describes the links between system state variables, management actions, and seedling establishment in woodlands within the Goulburn Broken catchment. This network forms the basis of the process model (BBN) and was developed by the project team, and refined during a workshop attended by an expert working group. This process follows the first three steps within an Adaptive Management framework (as outlined in Section 2):

i) The management objective

First, the group had to identify a measurable management objective that would form the basis of an appropriate monitoring strategy. This was based upon one of the extent RCTs described within the Regional Catchment Strategy (GBCMA 2003). The target aims to increase the extent of all threatened and endangered EVCs within the catchment to at least 15% of their pre-European cover by 2030. There are a number of finer-scale targets underlying this that refer to specific EVCs within the various bio-regions that require elicitation and one such target was developed for the purposes of this process.

The broad RCT mostly complies with the AM requisites but was modified to specify accepted uncertainty, a budgetary limit and a broad vegetation class (i.e., woodlands):

> To be 90% confident of having exceeded a target of 15% of the pre-European extent of threatened/endangered (non-riparian) woodland in the Goulburn Broken catchment by 2030, subject to a given budget.

The objective specifies both a target (15%) and confidence of exceeding that target (90%). For example, if we cannot be 90% confident that the 15% target is exceeded, this implies the management plan must change. Though the budget provides a constraint for the objective, it is in fact highly uncertain but required for effective allocation (Naidoo *et al.* 2006; Murdoch *et al.* 2007; Dorrough *et al.* 2008b). Constraints on this target could also be the potential regeneration area, the amount of seed/tubestock available for restoration, the availability of staff or a specified level of commercial output (Duncan and Wintle 2008).

ii) The performance measures

The next stage was to identify the primary performance measures that could be used to monitor the management objective (i.e. changes in woodland extent). In this case, the density of eucalypt seedlings was an obvious choice, as recruitment is already used to assess the effectiveness of management programs by the GBCMA (e.g. Bush Returns). Successful establishment of woodland requires the survival of eucalypts past the seedling stage, so a second performance measure was discussed. It was decided that a useful longer-term measure could be

Recruitment of eucalyptus seedlings in a former grazing paddock; the objective of the Bush Returns program in GBCMA. [Photo: David Duncan]

the density of saplings, which represents the density of seedlings that survive past the first year to grow beyond a sheep browsing height ('sapling escape', set at 1m). It was also decided that the scale at which these should be measured is at the paddock scale, in hectares. This represents the scale at which native vegetation management is generally funded in the Goulburn Broken catchment (i.e. on smaller blocks of private land). These measures are described in Table 1.

iii) Environmental factors

Third, a number of **environmental factors** that would influence seedling establishment and woodland establishment were identified. These were divided into two types of environmental factors; controlling environmental factors and intermediate factors. Controlling environmental factors (Table 2) are factors that control the environmental system at the nominated measurement scale (i.e. the paddock scale) but which cannot be modified at this scale (Cain 2001). Intermediate environmental factors (Table 3) can be modified by management interventions and are generally a function of the controlling environmental factors. They provide the link between the interventions and the management objectives (Cain 2001). Where possible, these variables can be quantified and tested, so the model can be updated with continuous monitoring data.

Table 1. The performance measures

Performance measure	Description
Seedling establishment	A continuous node describing the average density of eucalypt seedlings per m^2. A seedling is established if it is present after the first summer (conclusion of March). But if monitoring is not done at this time a seedling is considered as < 0.5 m height but past the cotyledonary stage (Vesk and Dorrough 2006). Seedling establishment is monitored within 3–5 years of management intervention at a site. Seedlings are measured per m^2 but this is monitored as an average on a paddock scale (i.e. > hectare). For an explanation of states refer to the variable 'sapling escape'. The states are: Success > 0.0075 seedlings/m^2 and Failure < 0.0075 seedlings/m^2.
Sapling escape	A continuous node describing the establishment of native eucalypts to "escape height" which is set at 1 m (saplings). This is measured as saplings/ha and monitored within 5–10 years after management intervention. 'Sapling escape' could potentially relate to the mature stem density benchmarks for the relevant EVC group (DSE 2008). At the moment success is set at 75 saplings/ha which is higher than the published benchmarks (generally around 25 mature stems/ha) but allows for an approximately 3:1 success rate for the sapling-to-tree transition. The states are Success > 75 saplings/ha and Failure < 75 saplings/ha.

Table 2. Controlling environmental factors

Environmental factor	Description
Land-use history	A discrete node that refers to the on-site land use only. The following states were identified: Improved = grazed + fertilized, or cropped + grazed in off season and Unimproved = unfertilized, can be either grazed or not grazed
Time since cropping	A continuous node describing time since the study area was cropped (in years). The state thresholds were determined based on the relationship between phosphorus retention in the soil (the child node) and time since cropping, and were derived from a paper by Standish *et al*. (2005). The rate at which the availability of soil P declines over time is uncertain, which is reflected in the wide temporal bounds assigned to each state. They are: Recent = 0–15 years, Mid = 15–50 years, Long = > 50 years
Time since grazing	A continuous node describing time since the study area was grazed (years). As above, the state thresholds were determined based on the relationship between soil compaction (the child node) and time since grazing, and were derived from a paper by Bassett *et al*. (2005). It is known that soil compaction declines relatively rapidly in the years immediately following land abandonment (Greacon and Sands 1980; Bassett *et al*. 2005; da Silva *et al*. 2008) However, the variability in compaction is shown to vary substantially until around 30 years (Bassett *et al*. 2005). Additionally, compaction varies with soil type (Greacon and Sands 1980) but this relationship is uncertain. The 'mid state' is given wide bounds to reflect this uncertainty. The states are: Recent = 0–3 years, Mid = 3–30 years, Long = > 30 years
Pr (natural regeneration zone)	A continuous node that describes the probability of a particular patch being within the regeneration zone. This is described using the paper by Dorrough and Moxham (2005), whereby distance to trees is allocated in 30 m interval classes. Using their calculations of the declining probability of seedling establishment with distance from mature trees, we estimate the following states: Near = 0–2 (i.e. 0–60 m), Mid = 2–4 (i.e. 60–120 m), Far = 4–6 (i.e. 120–180 m)
Short-term rainfall	This continuous node describes the probability of achieving one favourable rainfall event in the first five years after management is implemented (i.e. period over which we expect to see seedling establishment). A favourable rainfall event is the occurrence of a 'good' winter (April–September) followed by a 'good' summer (October–March) rainfall. The probability of achieving this must be greater than or equal to 0.2. According to the paper by Vesk and Dorrough (2006), who used rainfall conditions in the Bendigo region, a wet summer has > 275 mm and a wet winter has >395 mm. These thresholds are considered only a guide and can be modified for the study area.
Carrying capacity	This is a discrete measure of productivity for land being used for agricultural purposes and is expressed as the carrying capacity of the site. This is calculated using an equation published by the Department of Primary Industries (2005). Along with stock density, this node then determines the grazing pressure applied to the study site. The states are Low or High.
Post seedling establishment rainfall	This continuous node describes the presence of three favourable rainfall periods in the subsequent 5 to 7 years after seedling establishment (i.e. period over which we expect to see sapling escape is 10 years after management). A favourable rainfall event is one of either 'good' winter (April–September) or good summer (October–March) rainfall. If we consider there are 10 rainfall events in this period, the probability of favourable rainfall must be greater than or equal to 0.3. According to the paper by Vesk and Dorrough (2006), a wet summer has > 275mm and a wet winter has >395 mm. Again, these thresholds are a guide only and can be modified for the study area.

iv) Management interventions

Fourth, a list of common **management interventions** (Table 4) used within the GBCMA was described.

v) Compiling the network diagram

Last, the links illustrating the relationships between variables were established to form a network diagram. The variables that feed into other variables are referred to as parent nodes (the controlling environmental factors and management interventions), whilst the variables with links feeding in are called child nodes (e.g., the performance measures). It is possible to be both a parent and child node (intermediate factors).

Within the network diagram each variable is assigned a set of states which may be continuous states that have been discretised (e.g. Seedling Establishment, Table 1), or discrete states (e.g. Land-use History, Table 2). It is acknowledged that all the complexities of an ecological system are difficult to represent in a single model but it is important to keep the model simple whilst retaining system accuracy (Marcot *et al.* 2006). Thus, care was taken

Table 3. Intermediate environmental factors

Environmental factor	Description
Soil compaction	A continuous node describing the penetration resistance of a surface soil. The thresholds for each state are taken from estimates from various papers that describe the compaction threshold for seedling survival (Greacon and Sands 1980; Spooner *et al*. 2002; Bassett *et al*. 2005; Hamza and Anderson 2005; da Silva *et al*. 2008). This generally refers to establishment of crop or non-native species and is uncertain for eucalyptus seedling growth. The states are: No < 2 MPa Yes > 2 MPa
Nutrient status	A continuous node describing available phosphorus, measured as Colwell P (ppm). The threshold between reference and enriched is difficult to establish as high P values may be obtained from soils under trees in undisturbed sites (Prober *et al*. 2002a). The estimates given assume that an average available P for a site is calculated outside the canopy zone and is estimated from papers that compare P concentrations from cropped/improved land and adjacent long undisturbed sites (Standish *et al*. 2005; Duncan *et al*. 2008). The states are: Reference <15 ppm Enriched >15 ppm
Weed competition	A continuous node describing the average weed cover per m^2. The state threshold is estimated from a paper by Hobbs and Atkins (1991) that examines the relationship between weed cover and seedling establishment (child node). The states are: Low < 20% High > 20%
Seed availability	This is a discrete node which expresses the presence or absence of available seed, and is determined by the distance from mature trees, and the presence/absence of seed added via direct seeding. This is a difficult node to quantify, thus the states are just described as present or absent.
Grazing pressure	This is a continuous measure of grazing pressure that incorporates herbivore access, pest control, stock density and the carrying capacity of the site. Grazing pressure is expressed as a proportion, whereby stock density (recorded as dry sheep equivalent) is expressed in relation to the carrying capacity of a site. This node has uncertain thresholds, as it attempts to estimate kangaroo/rabbit pressure in relation to dry sheep equivalent. From the literature, a kangaroo is equivalent to 0.75 dse (Hacker *et al*. 2002). As a guide, typical minimum, median and maximum stock grazing densities for farms in the temperate slopes and uplands of central Victoria, Australia are described as 4.5 dse/ha, 8.2 dse/ha and 12 dse/ha respectively (Dorrough *et al*. 2007). The 'Rabbits/Roos' state predominantly describes grazing by kangaroos and/or rabbits but can be achieved with low stock and high carrying capacity. The states are summarised as: Rabbits/Roos < 0.3 Low = 0.3–0.7 High > 0.7

to restrict the number of variables and states to that which are thought to be most important and relevant to the objective at hand (Cain 2001; Marcot *et al.* 2006). The states defined within this model are where possible based on published benchmarks, but largely based on expert opinion (as discussed within the workshops) and derived from information within the literature (Pollino *et al.* 2007). The states our outlined in Tables 1 to 4, with more detail provided in the section describing the parameterization of the BBN.

Parameterising the model

The next step in the process was to develop the graphical network diagram into a BBN (Figure 4). This was done in the software package Netica (Norys Software Corp. 2008). In a full BBN the strength of the relationships between the child and parent nodes is described by assigning conditional probabilities to each state (Cain 2001; Marcot *et al.* 2006). A conditional probability table (CPT) was constructed for each of the child nodes which described probabilities for every possible combination of states from the associated parent nodes (Pollino *et al.* 2007). This was done to record how each child node changes in relation to its parents (Cain 2001). For instance, with reference to Figure 4, we might want to compare the probability of having high weed competition if we alternate between applying localised and broad-scale weed control (if nutrient state and soil disturbance are kept constant). As with the definition of states, the CPTs were parameterised primarily using information from the literature.

Table 4. Management interventions

Management intervention	**Summary**
Weed control	A discrete node describing the type and scale of weed control practices used. There is an assumption that certain species are targeted in localised weed control, whereas broad-scale weed control is widespread and also controls annual grasses. Removal of weed material is not specified at this stage, nor is the frequency of application. The states are: None = no control Localised = Hand spraying and hand picking Broad-scale = Boom spray, burn, or crash graze
Soil disturbance	A discrete node describing the presence or absence of soil disturbance actions. The practice of scalping, deep and shallow ripping is grouped in this node at present. This is because the choice between ripping techniques is presumably dictated by soil type. The states are: No = no disturbance Yes = shallow/deep ripping or scalping
Tube-stock planting	A discrete node describing the presence or absence (no/yes) of planting indigenous *Eucalyptus* tube-stock. Includes seedlings prepared using various methods (i.e. standard 50mm tubes, multi-cell trays). The method and density of planting is not specified at this stage because it is assumed that tube-stock planting always occurs at higher densities than that required to achieve a benchmark stand (i.e. Table 1). It is assumed that the practice of planting tube-stock disturbs the soil and alleviates soil compaction.
Direct seeding	A discrete node describing the presence or absence (no/yes) of direct seeding of indigenous *Eucalyptus* seeds. As above, the method (machine or hand) and density of seeding is not specified, and it is assumed seeding occurs at a higher density than that required to achieve the benchmark density.
Pest control	A discrete node that describes any sort of kangaroo or rabbit/hare control on site. Numerous methods are considered including culling or fencing for kangaroos, and culling or control of on-site rabbit burrows (collapsing, poison). We also consider the use of tree guards as a form of rabbit and kangaroo control. The states are: No = no control Rabbit = onsite rabbit control Rabbit_roo = onsite rabbit and kangaroo control
Stock density	This is a continuous node that considers the density of stock (Dry Sheep Equivalent, DSE) on an 'unfenced' site (i.e. site may be fenced but stock allowed in). It is difficult to define the exact thresholds as the impact of stock on site is presumably dictated by landscape productivity. However, a paper by Dorrough *et al*. (2007) describes a minimum stocking rate for farms in the temperate slopes and uplands of central Victoria, Australia, as being 4.5 dse/ha. A similar threshold of low stock density (5 dse/ha) is used in a study by Fischer *et al*. (2009). In the study by Fischer *et al* (2009), they define a 'low density' as equivalent to continuous grazing at a low stocking density or a rotational grazing regime. As such, the states are: Low < 5 dse/ha High > 5 dse/ha
Grazing exclusion	A discrete node that considers absence (no) or presence of fencing of site for either stock only, or for stock and rabbits. At this stage it is assumed that kangaroos will always have access, as kangaroo fences are uncommon. In the event that a site does have adequate kangaroo fencing (i.e. prohibits entry to site), this is included in the above pest control node.

Methods for filling in the Conditional Probability Tables

We used three methods to describe the conditional probability relationships between states (though see Marcot et al. 2006 for others):

1. Predominantly, we used probabilistic equations which are generally of the form:

$p(X|A,B,C) =$
$(A == State_{A1})\ \&\&\ (B >= State_{B1})\ \&\&\ (C == State_{C1})\ ?$
$NormalDist\ (X, 0, 1):$
Where:
X = child node
A, B and C = parent nodes, and
p(X|A,B,C): describes the probability of the child node, given the states of its parent nodes. "==" and "&&" are logical operators meaning <i>equals<i> and <i>and<i>, see Appendix 1 for more details.

$(A == State_{A1})\ \&\&\ (B >= State_{B1})\ \&\&\ (C == State_{C1})$: describes a particular combination of states for the parent nodes. The states can either be state names if the parent node is discrete (e.g. States A and C), or numerical if the parent node is continuous (e.g. State B). Note that the above equation is incomplete, as each combination of states must be accounted for. [A complete model is indicated by the term: 0.]

? NormalDist (x, 0, 1): describes the distribution from which the probabilities for x are drawn from,

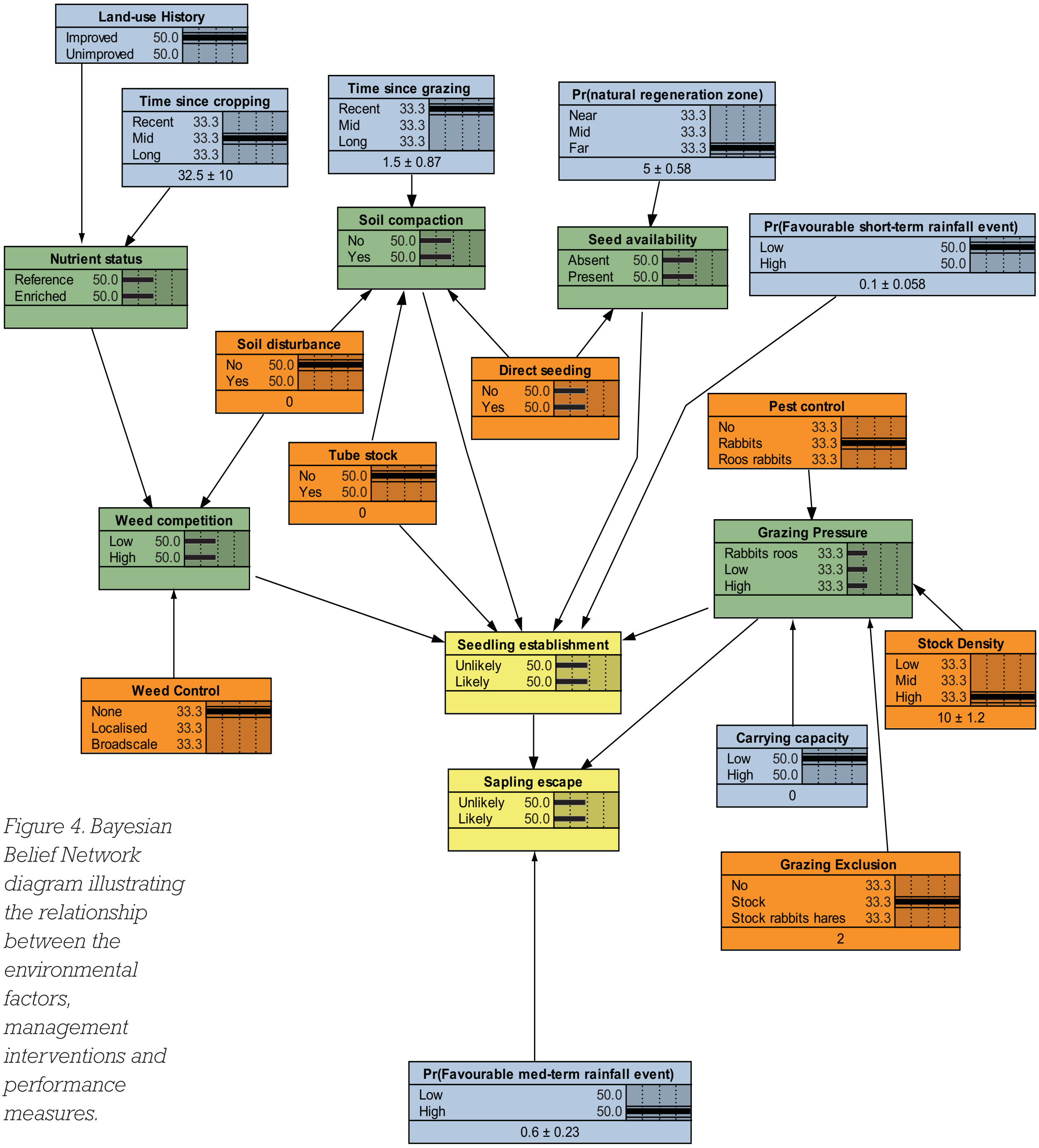


Figure 4. Bayesian Belief Network diagram illustrating the relationship between the environmental factors, management interventions and performance measures.

with a mean and standard deviation. In this example the distribution is Normal (NormalDist) with a mean and standard deviation of 0, 1 respectively.

2. Second, if a model containing the exact terms described in the BBN was found in the literature, it could be directly translated into the Bayes Net. For instance, a model may be of the form:
   $X\ (A, B, C) = A + B^{C}$
3. Finally, in some instances conditional probabilities were directly allocated to each state combination via the CPTs. For instance, if we use the example in 1, and assume each parent node and child node has two states, the relevant CPT would have 8 state combinations (i.e. 2 x 2 x 2), and is as follows:

Combinations of States			X1	X2
A_1	B_1	C_1	$= p(A_1,B_1,C_1)$	$= 1 - p(A_1, B_1, C_1)$
A_1	B_1	C_2	…	…
A_1	B_2	C_1	…	…
A_1	B_2	C_2	…	…
A_2	B_1	C_1	…	…
A_2	B_1	C_2	…	…
A_2	B_2	C_1	…	…
A_2	B_2	C_2	…	…

The equations used to populate CPTs referred to in this report are described in Appendix 2.

Reviewing the relationships within the BBN

Investigation of management scenarios

To demonstrate how the model works, we present scenarios for two different land-use histories which may be common in the Goulburn Broken catchment and alter the management interventions at these sites. We illustrate how the probability of each of the query nodes varies under these different management interventions over a five-year period. Query nodes are those we want to learn about and update, above the level of the response variables. In this case the query nodes are: Nutrient Status, Weed Competition, Soil Compaction, Seed Availability, Grazing Pressure and Seedling Establishment. These findings are presented for each scenario in Figures 5 and 6 respectively.

Scenario 1: Recently grazed remnant woodland

This is an unimproved area of native vegetation with a recent history of grazing. It is calculated that there is enough ground cover to constitute a high carrying capacity. The woodland has sufficient density of mature eucalypt trees per hectare such that the majority of the area is within 30 m of the natural regeneration zone (i.e. 'Near'). Rainfall has been low over the five-year monitoring period (i.e. there have been no years of favourable summer and winter rainfall). The effect of the following variations in management intervention at this site (a–c) is presented in Figure 5.

1a) No management intervention
(grazed at low density)

This is the reference case, whereby there is no management intervention at this site and it continues to be grazed by a low density of cattle. The probability of enrichment is low (16%), but with no weed control the probability that weed cover will exceed 20% is still high (74%). As the site has a history of grazing, the probability of soil compaction is high (95%). It is likely that grazing pressure is low given the high carrying capacity and low stock density, but this is dependent on the level of rabbit and kangaroo grazing at the site. Seed availability is reliant on the surrounding mature trees. The probability that we are likely to have seedling establishment under this natural regeneration scenario is around 19%.

1b) Fenced, localised weed control and rabbit control

This is assumed to be a general scenario for management at these sites. The site is now completely fenced off (stock only) for natural regeneration. Apart from fencing, the management implemented at the site includes localised weed control (i.e. targeted at removing Paterson's curse and thistles from the area), and collapsing of on-site rabbit burrows. This level of management intervention does not significantly affect weed competition across the site, but does reduce the grazing pressure to that of rabbits and kangaroos. This alone increases the probability that we are likely to have seedling establishment to 31%.

1c) Fenced, broad-scale weed control, soil disturbance, rabbit control and tube-stock

To increase the chances of natural regeneration at the site, money could be invested in broad-scale weed control and soil disturbance to ameliorate soil compaction and weed competition. Even though rainfall is low, there is now a 65% chance of having a likely scenario for seedling establishment (i.e. 75 seedlings/ha) over the three-year period from natural regeneration only. At this level of investment, all of the intermediate environmental factors which limit seedling establishment have been substantially reduced. However, maximising the chances of successful seedling establishment (to 94%) under a low rainfall scenario would require tube-stock to be planted. Planting a high density of seedlings at an advanced stage of development in part overcomes the lag in germination expected under poor rainfall conditions, though if these conditions continue the chance of sapling escape is only 32%. As a comparison, if direct seeding was used instead of tube-stock, the chance of successful seedling establishment increases by 10% (to 75%). Given tube-stock constitutes a higher cost, it may be that the direct seeding option is favoured in the event of predictions of poor rainfall for the following period.

Scenario 2. Recently grazed paddock with isolated mature trees and a history of sowing

This is a pastoral area that has been sown in the past (improved). It is calculated that there is sufficient ground cover to constitute a high carrying capacity. The paddock has a few scattered mature eucalypt trees but the majority of the site is considered 'far' from the regeneration zone (i.e., > 120 m). In the five-year monitoring period the rainfall was classified as low, whereby there were no years of favourable summer and winter rainfall. The effect of the following variations in management intervention at this site (a–c) is presented in Figure 3.

2a) No management intervention and grazed at high density

There is no management intervention at this site and it continues to be grazed by a high density of cattle. As such, grazing pressure is likely to be high (90%), despite a high carrying capacity. Given a history of continual grazing, the probability of soil compaction is also high (95%). The probability of enrichment is high (72%) and with no weed control the probability that weed cover will exceed 20% is still high (91%). Seed availability is reliant on the surrounding scattered mature trees and so on average there is a 22% chance there will be seed available for natural regeneration. The probability that we are likely to have seedling establishment under this natural regeneration scenario is around 4%.

2b) Fenced, broad-scale weed control, direct seeding (and soil disturbance)

Using the model it is evident a large amount of money has to be invested in the site to increase the chance of seedling establishment. For instance, fencing the site and implementing rabbit control only resulted in a 22% chance of successful seedling establishment. To ameliorate soil compaction (low = 100%), seed availability (present = 100%), weed competition (low = 100%) and grazing pressure (rabbits and roos = 90%) the site requires the following management interventions: direct seeding (with soil disturbance), broad-scale weed control and fencing. Under this scenario, the probability of seedling establishment (75 seedlings per hectare) is 70%. Introducing rabbit control only slightly reduces grazing pressure and as a result only increases seedling establishment to 73%.

2c) Fenced, broad-scale weed control, tube-stock planted (and soil disturbance)

The only way to substantially increase the probability of reaching the benchmark for seedling establishment of 75 seedlings per hectare would be to replace direct seeding with tube-stock. This increases the probability of seedling establishment to 82%. As a note, if rainfall conditions were favourable, this probability would increase to 90%.

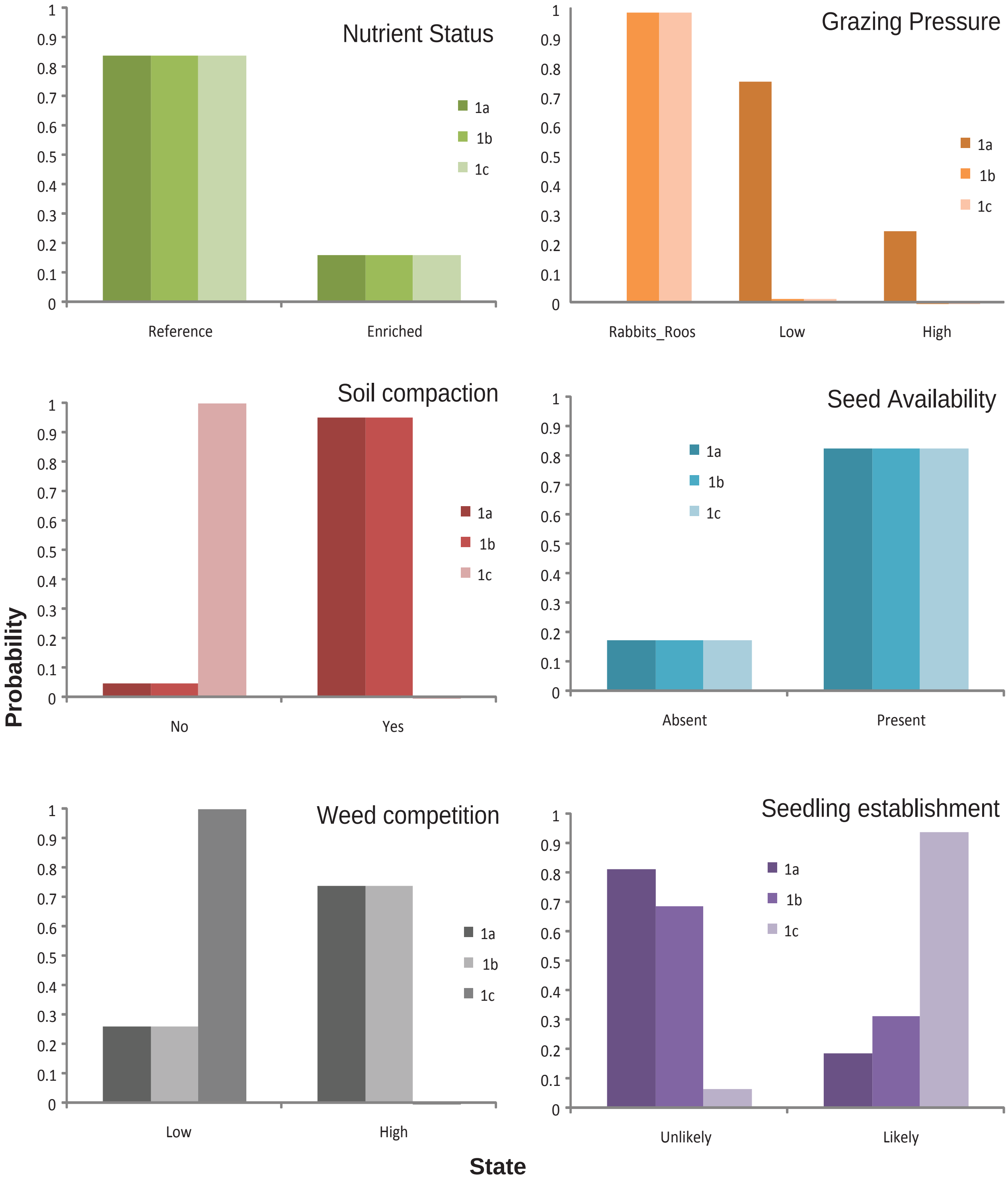


Figure 5. Predicted probabilities for the variables of management interest (Query nodes) under Scenario 1. 1a represents the point of reference scenario, whereby no management intervention is carried out at the site, and grazing by cattle continues at a low density. 1b is a commonly implemented strategy of fencing, rabbit control and targeted weed control. 1c is the higher cost intervention scenario, whereby the site is fenced and controlled for rabbits, but also undergoes broad-scale weed control, is ripped and has tube-stock planted.

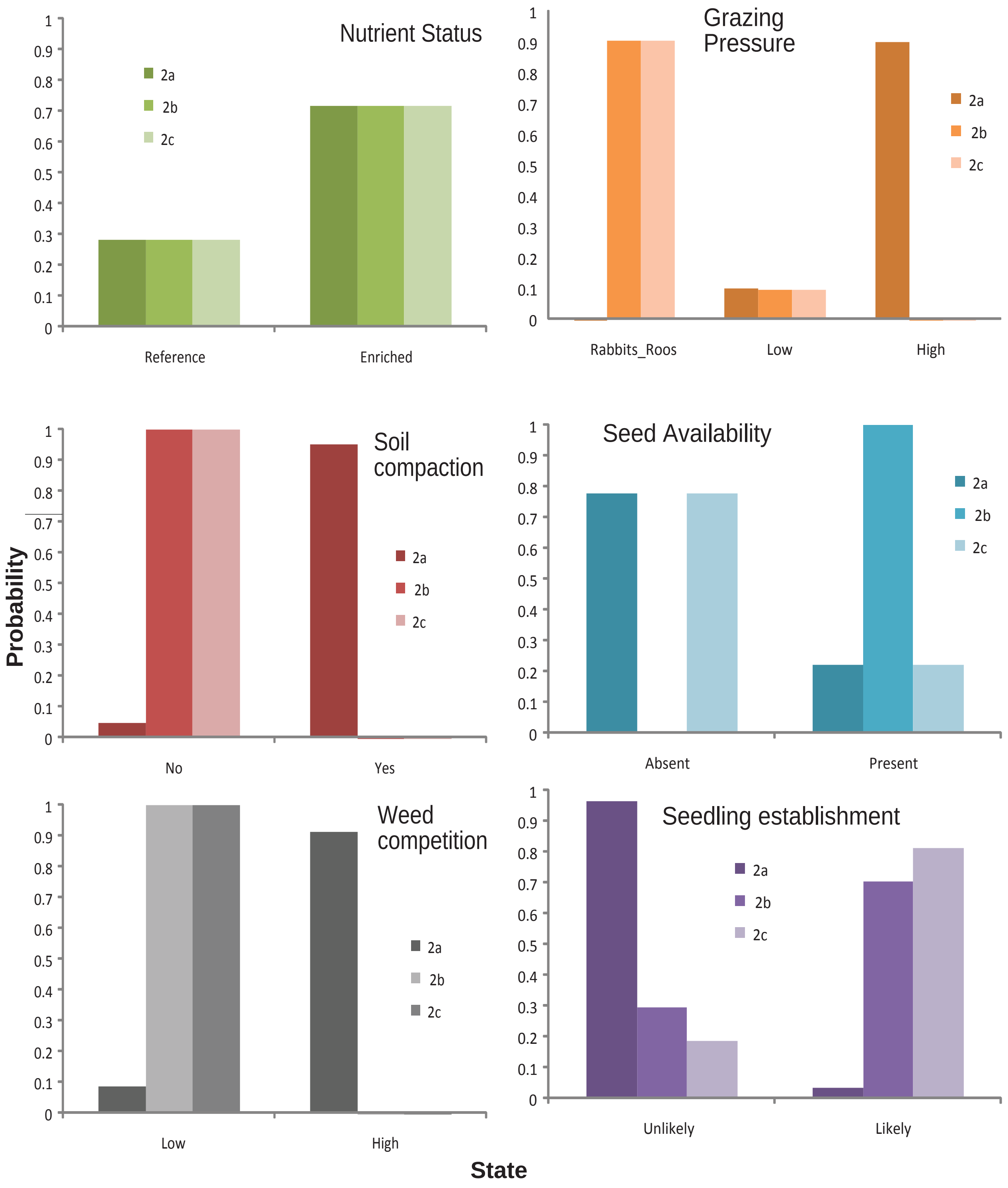


Figure 6. Predicted probabilities for the variables of management interest (Query nodes) under Scenario 2. 2a represents the point of reference scenario, where no management intervention is carried out at the site and grazing by cattle continues at a high density. 2b is when a substantial amount of money is spent and the site is fenced, direct seeded, controlled for weeds (broad-scale) and ripped. 2c is similar but direct seeding is replaced by tube-stock.

Data collection and monitoring

Introduction

In Section 3 we described a process model representing our beliefs about the management options that maximise the probability of restoration success under different management and climate scenarios. The starting model is essentially a hypothesis and in adaptive management we update our model as new information becomes available. This new information could come from studies that occur outside of the modelled ecosystem. For example, a new study of eucalypt recruitment in a different woodland community elsewhere in Australia might offer new insights about the relative importance of soil compaction on seedling recruitment. However, the most efficient way to add relevant new data to improve the model is to monitor the variables represented in the model within the modelled ecosystem.

We can control the rate at which we learn about our system and therefore the expected time until we can confidently evaluate the effectiveness of management, through decisions about the frequency and precision of data collection. In natural resource management and conservation contexts favoured assessment techniques are simple and as accessible as possible so that minimal technical expertise is required for their implementation. The implication of trying to use such a technique for monitoring may be an unacceptably slow learning rate caused by highly uncertain data. The time and resources that will be required to serve the monitoring function also depend upon the effect size of interest and our requisite degree of certainty. For example, do we need to be 100% certain of an effect in order to trigger management action or will 80% be persuasive to the key stakeholders? In this section we illustrate some of these key considerations using examples relevant to the process model described in the previous section.

Data collection

Data requirements

How many samples are needed to detect change over time? This question is encountered with every monitoring project. Most often, ad hoc numbers or rules of thumb are used, but a good answer requires a clear statement of the management objective, including what magnitude of change in our response variable we are interested in.

In many of our monitoring problems we are interested in change of some variable(s) through time (i.e. the performance measures). As a conceptual illustration of the problem, consider a variable (e.g. seedling density) that we estimate with some

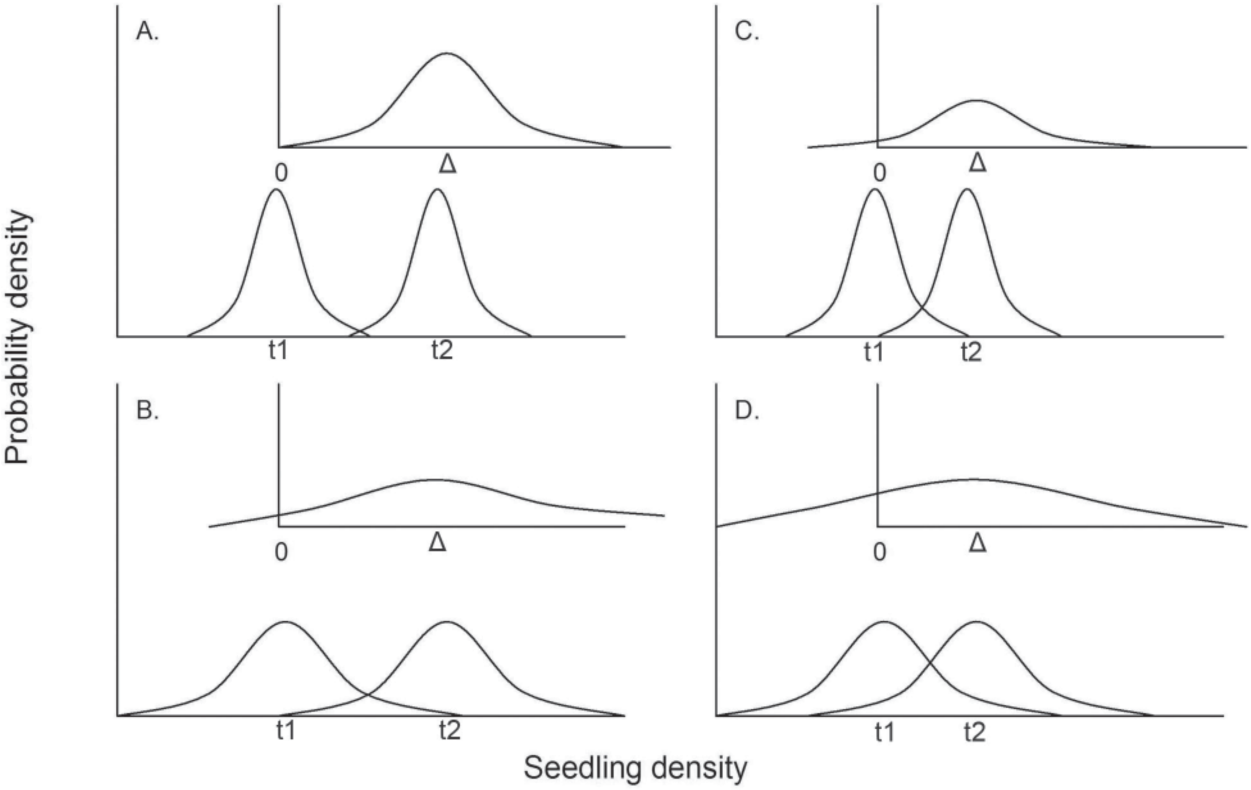


Figure 7. Estimation of the magnitude of change (Δ, inset graphs) between two time periods (t1, t2) as affected by magnitude of the change (larger in A and B, smaller in C and D) and our imprecision in estimation (relatively precise in A and C; imprecise in B and D)..

precision at two times (Figure 7). Bell curves represent the distribution of values this variable may take. We are interested in the change between the two times, which is represented in the inset graphs (Figure 7A–7D). The farther apart the two estimated distributions, the greater the change, and so the further the change distribution is to the right. The greater the overlap between the two times, the more of the change distribution is to the left (< 0).

Now the variables are estimated with some level of uncertainty. The less certain we are about the estimates at each time, the less certain we can be about the magnitude or direction of the change. In the base case, Figure 7A, the two distributions are almost non-overlapping and the change distribution is greater than 0. If our uncertainty is greater (i.e. due to small sample size), then the overlap is increased and the change distribution extends from small decreases (< 0) to large increases (Figure 7 B). By contrast, if our uncertainty is unchanged but the magnitude of the change is reduced, the overlap is also increased (relative to the base case) and the change distribution extends from small decreases to moderate increases (Figure 7C). In the worst case of a small change and great uncertainty (Figure 7D) the overlap between the samples is large and the change distribution extends from large decreases to large increases. In other words, we cannot be sure of anything. This illustrates how both the magnitude of the true change and our uncertainty about that change can affect our estimated change (or our performance).

To answer the question "how many samples", we need to know 3 things:

(1) How large a change we want to know about (our important effect size);

(2) Our tolerance for error about that estimated change;

(3) The expected sampling variation.

After defining these three things we can provide useful answers to the question of required sample size. Here, we describe an approach that proceeds as follows:

1. Define the objective with an appropriate response (or performance) variable;
2. Provide an interpretation for values of the response reflecting qualitatively different levels of performance (e.g., coloured bands in Figure 8);
3. Simulate "true" changes in the response;
4. Simulate estimation of those changes with different sampling designs;
5. Choose a sampling design that allows discrimination between different qualitative performance levels, or return to 2 (above) and revise the interpretation if the logistics of the sampling cannot be met (constrained budget). Then select the sampling design that allows discrimination between the revised performance levels.

The essence of the procedure is choosing a measurable (quantitative) response variable that indicates ecological performance (e.g. number of recruits, percentage cover of a plant, population size, extinction risk, etc). This is as specified in Step I of the AM framework. This forces us to think about what is good performance, it provides clear interpretations of ecological responses and it provides the template for precision requirements of sampling. Then we proceed to model sampling effort under different scenarios and review our desires and appropriate designs. Below we use a worked example to illustrate this approach.

A worked example of monitoring design considerations using Green Graze data

In the Green Graze Incentive Trial being run by GBCMA, a particular interest is in fostering natural regeneration of tree cover. The potential regeneration area is thought to be the area within 60m of extant mature tree canopies. The density of seedlings (number per unit area) declines quasi-exponentially away from tree canopies and is negligible beyond 60 m. One possible objective for the trial is to maximise the density of seedlings across the potential regeneration areas. As such, we will examine how we can assess performance toward this objective. Broadly, the design can be described as sampling initially to estimate current seedling densities, then sampling again in 10 years time and determining the magnitude of change. (Note, the analysis examined here is not a repeat measures design on permanent plots—this is considerably more complex to implement and to describe).

It is expected that up to 80% of the potential regeneration area on Green Graze sites will be actively regenerating in 10 years (Carla Miles, Pers. Comm.). This suggests a relevant response variable or performance measure is the increase in the occurrence or density of seedlings over the ten-year period. We will use density for this example. It should be noted that we are interested in a multiplicative increase rather than an additive increase: it makes sense to think of a doubling or tripling of seedlings rather than 20 or 50 more. For simplicity, we will make predictions about the mid-point of the potential regeneration zone which is 30m from the canopy edge. We have some data that suggests current densities are about 0.25 seedling /quadrat at 30m from the edge of tree canopies. For 80% of the area to be occupied the density of seedlings at 30m needs to be considerably greater than 0.8. This value might suggest that if you had 100 quadrats, 80 would contain a seedling if they were evenly distributed (noting that seedlings tend to be clumped and quadrats close to 60 m from canopies will have lower densities). We wish to know how many quadrats are needed for us to establish whether we are making good progress toward our objective or not.

Interpretation of the response scale

To guide our sampling design we need to provide an interpretation of our response variable (change in seedling density). That is, what do the various values that might be observed mean to us? One way to do this is to specify intervals along the response variable as having different values (Figure 8). For instance, if over the 10 years the density of seedlings did not at least double, we might consider this **poor** performance. Similarly, if the density of seedlings was at least 3.5 times the initial density, we might consider this a **good** outcome. In between these values we might consider a **fair** outcome. This step is important for developing biological and management interpretations of values for our response variable (or performance measure). If we divide this response variable more finely we demand greater precision in our estimates. If we divide the response more coarsely (e.g., improvement vs. little change) then less precision is required. Precision is determined by the inherent variation in the system (i.e. how densities vary across space) and our sampling design, here simply the sample size.

Simulation of collecting data and estimating change

Our variable of interest is the multiplicative increase in density of seedlings at 30 m from trees. We observe these in 15 x 15 m quadrats (225 m^2). We have data from approximately 70 quadrats, which we can use to estimate the density of seedlings and its variability. We use those data to simulate increases of various magnitudes – these give us the true change. We then simulate sampling quadrats and use these samples (different sized: *n* = 60, 100, 180, for instance) to provide an estimate of the change. This gives us one estimate but we do this many times to generate the distribution of expected changes. This provides plausible values for the change calculated under known scenarios of increase in seedling density and known sample size.

We simulated four scenarios of increase (1.5 x, 2.2x, 3.3x, and 5.0 x) from 0.25 to final densities of 0.37, 0.55, 0.83 and 1.23 seedlings per quadrat, respectively.

Figure 8 illustrates how placing qualitative interpretations on a quantitative scale (i.e. specifying

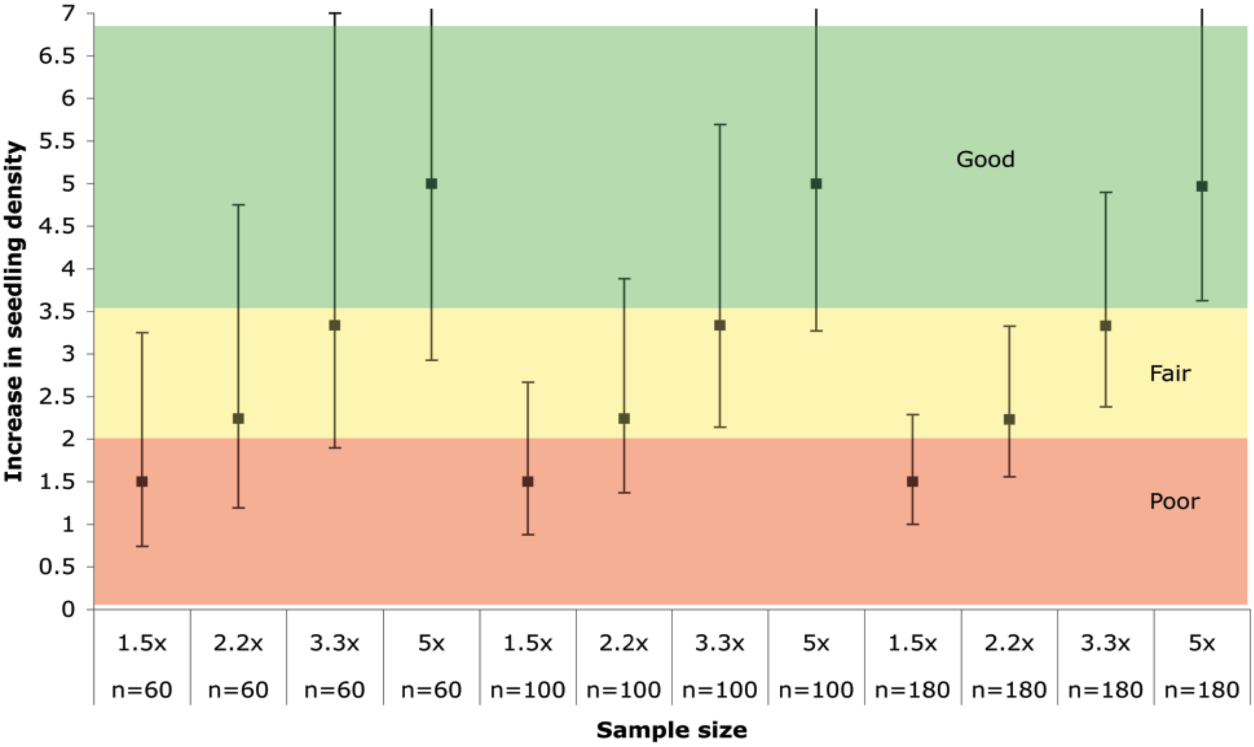


Figure 8. Effects of sample size and magnitude of change on estimation of change in seedling density or performance. The squares represent the median and the bars the 95% credible intervals for the expected estimates of change. The X-axis represents different scenarios of true change and sample size; these are grouped by sample size and ordered by magnitude of change. The Y-axis represents the change in seedling density. The differently coloured zones represent different classes of performance. Smaller samples produce less certain estimates of change, spanning multiple classes..

important effect sizes) enables the evaluation of various change scenarios in simple terms. The symbols represent the means of all our simulations and are effectively indistinguishable from the true response. Overall, we see that the expected estimated change increases with the modelled change, the range of plausible values increases with the magnitude of the change, and the range of plausible values decreases with increasing sample size.

Let us begin with the left-most scenario for sample size of n = 60, beginning with the smallest modelled increase, 1.5 times the initial value. In this scenario, the most probable estimate for the change is 1.5, which we interpret as poor. But we might estimate the change as being as great as three times (a fair outcome) or as little a decrease to 75% the starting density – clearly a poor outcome. The next two scenarios (2.3x, 3.3x, both n = 60) represent the undesirable situation where plausible values range across the three intervals, meaning that we might recover estimates that support interpretations of each of poor, fair or good performance. For all of these modelled changes the range of plausible estimates overlaps considerably. This suggests 60 quadrats is clearly not a big enough sample size. In fact, even if we were to reduce our precision requirement by recognizing only two qualitative performance levels, good and bad (delimited at 3x), we still would not be confident that our sampling would result in an accurate result.

Let us now examine samples of n = 180, the right-hand group. In no case do we see the range of plausible values spanning three performance classes. In addition, the ranges of plausible values have considerably smaller overlaps; the 1.5 and 3.3x bars do not overlap, nor do the 2.2 and 5x bars. The right-most scenario (5x, n = 180) would result in unambiguously good performance. However, smaller changes could still result in estimated changes across two classes, even with 180 quadrats. If we were to just recognise two classes delimited at 3x, as above, the smallest true change would be reported as unambiguously bad performance, while the largest modelled change would be reported as unambiguously good performance. Our intermediate changes could still result in mean estimates falling into both performance levels.

This example illustrates how we can use our knowledge and management goals to develop meaningful qualitative and quantitative performance measures and, complemented with modelling of possible changes, develop appropriate sampling designs. This approach could be used for a number of monitoring attributes, including other vegetation or habitat attributes e.g., volume of logs, percentage cover of shrubs. A similar approach could be used for fauna, with variables such as the occupancy or richness within a functional group of birds across sites.

A couple of notes on this example

First, these graphs represent the range of plausible values for the estimated mean change over the specified sample of 60–180 sites, using only the mean for each site. When the data is analysed, the variation around each site that mean should also be estimated to yield a range of plausible values, given the observed data. Consequently, a different mean and interval would likely result from the real-world sampling and this interval may extend to lower or higher values than indicated by the simulated intervals in Figure 8.

Second, this example assumes independent samples. That is, the quadrats in the second sample period are not in the same location as those from the first sample period. A better sampling design would be to use permanent plots and to measure change within these because the variation from place to place would not confound the change through time. We did not use this approach here because the simulation for a permanent plot analysis would require more assumptions about the processes of birth, death and successful recruitment.

Third, while we modelled seedling density, the analysis could be done with the probability of seedling presence. This might be better linked to the aspirations of expanding tree cover as greater density is not necessary, and possibly even counter productive, to expanding cover. It is also less affected by clumped distributions of seedlings. However, we chose not to use occupancy because there is more information using a density example and because the interpretation of change is marginally simpler. For instance, compare a three-fold increase in the number of seedlings per quadrat is more easily interpreted than a three-fold increase in the odds of observing a seedling in a quadrat.

Fourth, this example has considered the difference in the seedling density between two times. One could just as reasonably measure the rate of change through time. In such a case, sample size requirements may be smaller if we wait longer before we sample, or if we sample in multiple years.

Monitoring of management performance

One of the advantageous aspects of implementing the process model within a BBN is that support for monitoring and updating of information is readily available. Monitoring data is collected and incorporated back into the model to update the original relationships expressed in the CPTs . These updated CPTs continue to reflect the state of knowledge across a range of sites in the Goulburn Broken catchment. The models presented identify appropriate measures and environmental variables to add to a monitoring strategy. For instance, in the seedling establishment model we identified the management outcome of interest, getting seedlings and saplings established and also identified the environmental variables that are likely to control this outcome. Ideally, all variables (as identified in the models) will be included in the monitoring strategy to enable learning of the system response to management. However, it is acknowledged that this is unlikely given some variables are unknown, or too time consuming and expensive to collect routinely. The following suggestions are made with regard to the design of a monitoring strategy.

1. Basic site data should be collected at the initiation of the monitoring site. This includes information on the controlling variables (e.g. land-use history, proximity to natural regeneration zone) and the management actions to be implemented. Most of this information may be obtained from the landholder. Some of the historical information may be unknown but the model is able to cope with incomplete data sets.
2. All the performance measures should be measured repeatedly over time. The benefits of learning (i.e. rate of updating) will be delayed if only a subset of these variables is measured. In the worst case, it is possible that the predicted outcome (e.g. state of vegetation condition) could be incorrectly estimated if a subset of variables is monitored, which may result in poor management decisions.
3. As the current state of knowledge of system response is not well advanced, we advocate that as many as possible of the remaining variables in the model (i.e. the intermediate environmental variables) should be monitored until our knowledge of system response is satisfactory. Given the potentially high expense associated with this, a better option may be to establish a set of intensively sampled baseline monitoring sites across the landscape that are dedicated to learning. Other sites may have a subset of variables monitored (i.e. performance measures and management actions as a minimum).

The expectation is that the frequency and number of monitoring variables will decline as we identify variables that contribute little to describing system dynamics and that have little influence on decisions about most efficient management. These variables can be removed from the working BBN to reduce its complexity. However, if these variables may one day become important due to changing environmental conditions, then it is ideal to leave such variables in the model. This process also enables learning about whether the thresholds used in the model are appropriate, which is likely to evolve over several iterations of monitoring data collection. The structure of a BBN can readily be altered after a period of time to incorporate additional data or new knowledge.

Implementation of management actions and allocation of resources

We can also use the BBN to answer several other questions about resource allocation and management decisions, such as:

- Which sites can we select to get a high likelihood of seedling establishment?
- Given a particular site history which management actions should we do to improve our chances of getting seedling establishment?

In the first instance, the seedling establishment model can be used to identify sites which have the greatest chance of seedling establishment. This is explored partly in the analysis of the scenarios in this report (Figures 7 and 8), which indicated that sites such as those presented in Scenario 1 (remnant woodland) are more likely to have successful establishment of seedlings compared to sites such as those in Scenario 2 (improved pasture).

There may be a decision to focus on remnant woodland sites or abandoned native pasture (i.e. varying tree densities) as it presents a lower cost option and a higher success rate. However, if we are concerned with increasing the cover of trees across the landscape we might focus on those sites which may not have a high density of mature trees, which are typically found in improved pasture scenarios. Alternatively, these sites may represent endangered woodland communities that are biodiversity funding priorities. In either case, we can use the model to identify the types of management intervention required to achieve seedling establishment at these sites.

An acceptable likelihood for seedling establishment or sapling escape can be discussed and then the model can be used to decide on the most cost-effective range of management interventions required to reach that target. Ultimately, if we can be explicit about the trade-off between protecting endangered communities and increasing canopy cover (for example), we can use the BBN as a basis for a cost–benefit analysis.

Alternative models of native vegetation change

Introduction

In Section 3 we described a process model representing our beliefs about the management options that maximise the probability of restoration success under different management and climate scenarios. Focusing on seedling recruitment was one approach to the system simplification that model building demands. However, it is certain that different sections of the community and different stakeholders have different ideas about the purpose for management of native vegetation. Rather than seedling recruitment, a fire management agency might want to focus on fire fuel loads above all other considerations. A bird observer might care about the provision of crucial food and nesting resources for birds. These are examples of alternative but still relatively simple purposes for which performance measures are relatively tractable. By contrast, the typical focus in Victoria is to manage native vegetation for the multiple objectives of structural complexity, species and life form diversity and ongoing recruitment, as reflected in vegetation condition metrics (Parkes *et al.* 2003; Gibbons *et al.* 2005). In this section we briefly explore process models which – with further development and validation – might be an appropriate centerpiece for an adaptive management framework based on two of the above examples. The first describes a state and transition model for vegetation condition, the second a model which examines the habitat requirements for woodland birds. Both models have been represented in the Bayesian Belief Network framework, like the seedling model in Section 3; however, they represent developmental products only.

A model for vegetation condition

From a system modelling perspective, an approach that identifies simple performance measures is ideal. Management of native vegetation condition is far more complex. There is no single agreed definition of native vegetation condition; however, in the language of Australian government policy, native vegetation condition is a multiple objective that seeks to promote mature, structurally and functionally diverse native vegetation communities to maximise habitat potential for native species (Parkes et al. 2003). Developing a quantitative process model of the system in this context is particularly challenging. In the next example, we describe a state and transition modelling approach to vegetation condition modelling.

A state and transition framework

State-and-transition models (STM) can potentially provide a very powerful approach to modelling ecosystem dynamics. They are conceptually easy to grasp and have been extensively used in rangelands vegetation management in North America and elsewhere (e.g. Westoby *et al*. 1989; Bestelmeyer *et al*. 2003; Bestelmeyer *et al*. 2004; Hobbs 2009).

A state and transition model is one in which the different states of native vegetation condition that may occur are identified and delimited. Hypotheses regarding the factors which may drive transitions between states are also defined (Westoby *et al.* 1989). One of the values of a state and transition framework is that it describes sites and investment strategies in a way that is likely to be seen by managers, rather than on a strictly ecological basis (Westoby *et al.* 1989). For instance, managers can identify degraded states that have a limited capability to achieve a high quality restoration target. However, observing change within the landscape according to the states alone can be problematic because the definitions are coarse and it is impossible to get a measure of how the condition of individual performance measures are tracking within the states. A problem arises when a site may be in decline but this goes undetected until it has changed to a poorer quality state. As an example, there may be a slow decline in species richness at a site, not enough to trigger a transition to a more degraded state, but nevertheless may be of concern to a manager. Picking up on these changes earlier with a more quantitative approach means that management can be implemented to halt or reverse the process.

The framework presents a series of different states of native vegetation condition that can be identified in the landscape and illustrates all the possible transitions between states. To enable a quantitative approach requires the states to be defined in relation to attributes of vegetation condition (i.e. structural, functional and compositional attributes). States are thus defined in relation to thresholds for each of these attributes (e.g. species diversity, weed cover, canopy cover etc). These attributes (or state variables) are the performance measures of interest. State changes are determined by a change in the value of these variables, as triggered by the combined or independent influence of a change in environmental conditions, land-use type and intensity. A transition from one state to another indicates the value of the state variables has reached some threshold, resulting in a qualitative shift in vegetation structure and composition.

In the Network Diagram (Figure 9) we present change in these individual vegetation condition

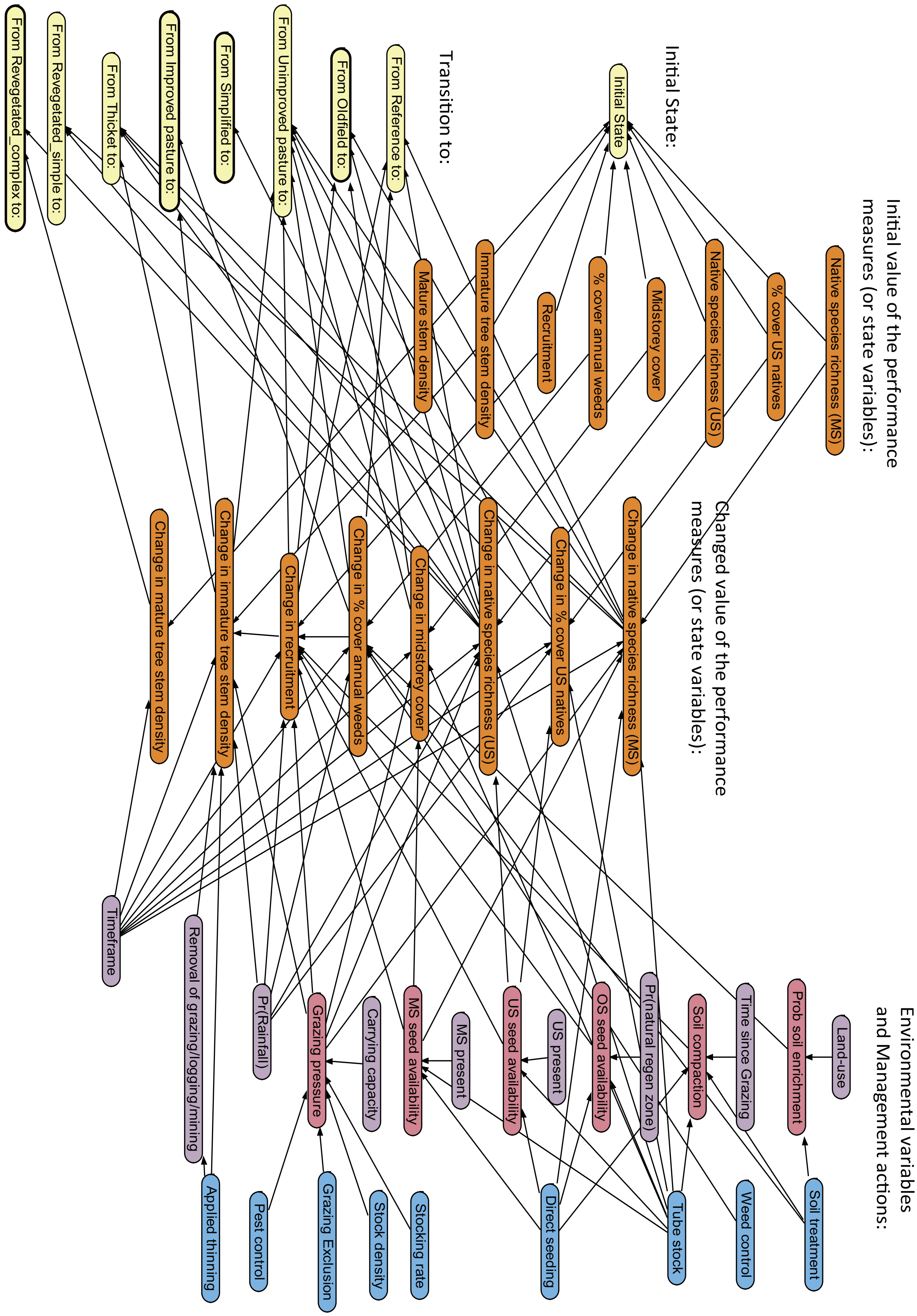


Figure 9. The Bayesian Network Diagram illustrating a state and transition model for vegetation condition. It illustrates the relationship between the controlling/independent environmental factors (purple nodes, which includes time), environmental factors or process variables (pink nodes), management interventions (blue nodes), performance measures/state variables (orange nodes) and initial state and state transitions (yellow nodes).

variables (performance measures), thus illustrating how those variables may be changing without really causing a shift in the overall 'status' of the site as appreciated by managers/investors. We also group the performance measures into one node (the states), which conceals the magnitude of change in the individual performance measures but illustrates the transitions between states. Incorporating a state and transition model into a BBN is potentially a useful format in which we can both learn about the effect of management intervention on vegetation condition across the landscape, whilst presenting a practical way for managers to report on vegetation condition change.

A model for fauna

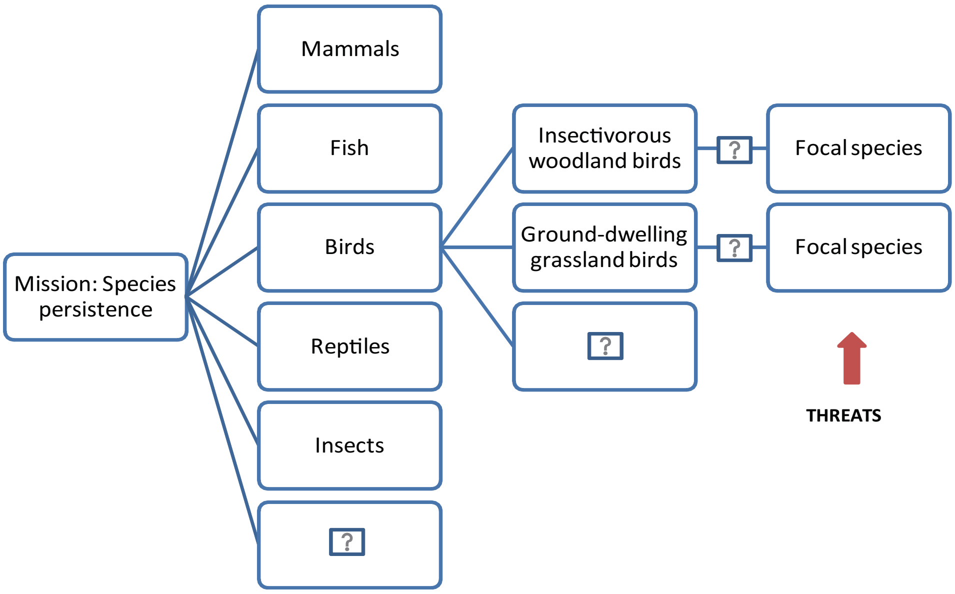
There is still little understanding of how the Resource Condition Targets ensure that faunal biodiversity is preserved or improved across the catchment. At present, there is an assumption that meeting the management targets for vegetation extent and condition will ensure the persistence of fauna but this is untested. Thus, a greater understanding of the structural, compositional and spatial habitat components that are required for fauna is needed (Lambeck 1997). This can be partly resolved by developing process models that link fauna to habitat variables.

First, there must be some discussion on how management objectives and monitoring programs can be developed for fauna in relation to the mission of species persistence. For instance, what is it about faunal biodiversity that we actually care about (everything?), and how do we measure and monitor these things? To assist in this process, the goal of preserving 'faunal biodiversity' can be broken down into more specific management goals (i.e. birds, mammals), as illustrated in Figure 10. These classes may be broken down further depending on how we manage habitat. For example, there may be interest to preserve all native bird species but the management strategy for ground-dwelling bird species is likely to be very different from those that exist in tree hollows within the canopy. Thus, as in the above example for vegetation management in relation to the Resource Condition Targets, there exists a series of finer scale objectives underlying the broader target of ensuring species persistence.

As an example, we could structure a process model for the specified objective of ''attaining self-sustainability in populations of insectivorous woodland birds in the Goulburn Broken catchment'' (Figure 11). As in the example for Floodplain Woodland, within this objective there would also be specification of an accepted level of uncertainty for detecting change over time, identification of trade-offs or constraints (i.e. budget) toward achieving this objective and a time-frame (i.e. within 50 years).

The target implies all insectivorous woodland birds will be managed to attain self-sustainability. However, it is not always practical to measure and monitor all species, and alternative means must be identified. An alternative may be to measure a reduced set of species that represent the needs of the broader faunal group(s). These species are termed 'umbrella' or 'focal' species (Lambeck 1997; Figure 10). As mentioned above, it may not be possible to use one focal species for birds, as the habitat requirements for birds can vary enormously (see Watson *et al.* 2001). However, it might be possible to use one focal species to represent the needs of other faunal groups with the same habitat requirements. Such approaches have been suggested before (Lambeck 1997) but are potentially very complicated and require testing. In the context of the Biodiversity Mission, it would be necessary to identify a suite of focal species to capture the different

Figure 10.
An example of how we might identify multiple management objectives for fauna in relation to the Biodiversity Mission. A suite of focal species that are susceptible to particular threats and thus will respond to management, may be used as representatives of other faunal species/groups with similar habitat requirements in the monitoring process.



habitat requirements of fauna across the catchment.

The identification of these focal species is a challenging prospect. It can be done by ranking species according to their susceptibility to threats that impact on resource availability, dispersal, habitat size, or processes (Lambeck 1997). Species most susceptible to these threats are chosen (and monitored), and can be used to determine the intensity of the management actions that ameliorate the threats over time. It may be necessary to use more than one species to cover all threats (Lambeck 1997). Focal species might be proposed based upon expert opinion or scientific studies but the assumption that a particular focal species is in fact representative of a group of species across a landscape requires rigorous testing.

In the example for insectivorous birds (Figure 11), the performance measures (yellow nodes) for these focal species may be as follows:

- Birthrate/Recruitment
- Mortality
- Immigration (Habitat extent)
- Number of individuals
- (Diversity of woodland birds).

Birth and death rates are measured to establish what state the population is in and how we are progressing toward 'self-sustainability' of the population. Immigration is expressed as the probability of birds being able to immigrate into a site, which is dependent on both existing remnants and revegetation activities. Thus, habitat extent is used as a surrogate for immigration. The last measure, bird diversity, is required at least initially to test the assumption that the focal species identified is representative of bird

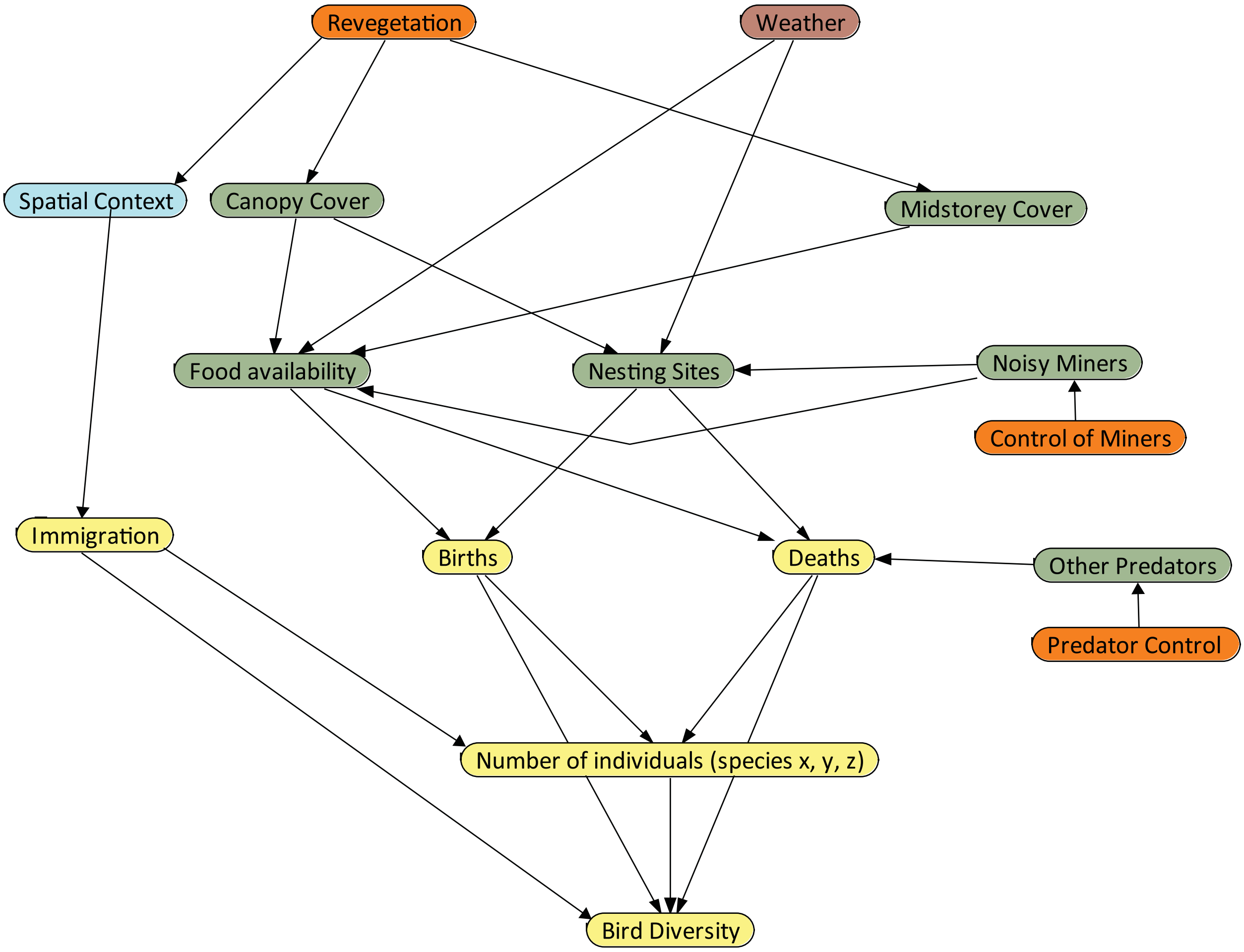


Figure 11. From Step I, our overall objective is to ''attain self sustainability in populations of insectivorous woodland birds in the Goulburn Broken catchment'' over a particular period of time (i.e. in 50 years). In this instance we are monitoring bird diversity on a patch level. Sites occur at different distances to neighboring native vegetation patches (blue node) and are subject to a particular set of weather conditions in the previous time period (brown node). The management options that may be implemented at this site are illustrated in orange and the system variables influenced by these actions (and by the starting conditions) are illustrated in green. There are five performance measures in this situation (the yellow nodes) which may be monitored in conjunction. Monitoring data may then be used to update the model conditional probabilities.

diversity as a whole. Even if it is decided that diversity should be used as the performance indicator to monitor over time, it would still be useful to monitor the population size of a few species in conjunction. For instance, if we are measuring diversity at patch scale, it is likely that diversity will be extremely variable across patches and the average may not give us a good sense about how diversity is changing over time.

The performance measures are thought to be influenced by the following biophysical variables (green nodes); canopy cover, mid-storey cover, the availability of nesting sites, food availability, the presence of Noisy Miners and predators (e.g. foxes), spatial context (i.e. proximity to neighboring habitat) and the weather conditions in the preceding years. To impact on these variables, the management options specified could include any combination of fox-baiting, control of Noisy Miners, or revegetation. Each of these options could include different levels (or types) of action. In this instance, the optimal revegetation strategy is assumed under the revegetation option. To inform this node requires information to be added from a BBN that deals with optimal management for woodland vegetation, such as the example above for floodplain woodland (Figure 4). Thus, it would be useful to create co-existing process models for fauna and at least the broad vegetation community of interest.

In summary, we may be able to use these process models to detect and monitor important habitat components for fauna. In relation to the Biodiversity Mission, it is anticipated that a number of process models would be required to address all of the faunal groups of interest. Following from this, the habitat requirements are likely to vary substantially, as are the potential management options. To reduce confusion in the process models for fauna, it is suggested that separate process models that identify optimal vegetation management strategies are used to inform the fauna models.

Conclusion

In this report we outlined the key elements of an Adaptive Management (AM) framework and how the framework might be applied to the task of managing native vegetation in GBCMA. Under such conditions of complexity and uncertainty, the role of process models in anchoring an adaptive approach is critically important. We illustrated the development of several such models that link performance measures to their environmental and management drivers using Bayesian Belief Networks. We parameterised a model of seedling establishment as one example using existing knowledge from relevant systems within and outside GBCMA. We also included examples of first-cut system models (or process models) for seedling establishment, vegetation condition and bird diversity.

These BBNs represent beliefs about what leads to successful seedling recruitment and can be used to support the design a more informed management and monitoring strategy (i.e. Step 4 of the AM framework) for the GBCMA. Further model validation against data and local experts will help to increase confidence in the model and allow for improvements to be incorporated.

The model improvement and updating cycle is fundamental to the logic of the adaptive system. We have endeavored to demonstrate by way of worked examples how data quality feeds into capacity to draw confident conclusions and we highlighted some important data collection considerations. This includes the identification of appropriate measures and environmental variables in which to add to a monitoring strategy, how we might use the model to identify which management interventions are required at a given site, and how we can use the subsequent data collected in a monitoring strategy to learn about the relationships and thresholds used in the models.

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Appendix 1: Common Symbols used in this report (Norys Software Corp. 2008)

Functional notation	Operator notation
neg (x)	- x
not (b)	! b
equal (x, y)	x == y
not_equal (x, y)	x != y
approx_eq (x, y)	x ~= y
less (x, y)	x < y
greater (x, y)	x > y
less_eq (x, y)	x <= y
greater_eq (x, y)	x >= y
plus (x1, x2, ... xn)	x1 + x2 + ... + xn
minus (x, y)	x – y
mult (x1, x2, ... xn)	x1 * x2 * ... * xn
div (x, y)	x / y
power (x, y)	x ^ y
and (b1, b2, ... bn)	b1 && b2 &&.. && bn
or (b1, b2, ... bn)	b1 || b2 || ... || bn

Appendix 2: Justification and equations for the model nodes

Nutrient status

p (nutrient | history, time2) =
(history == Improved) && (time2 >= 0 && time2 <=15) ? NormalDist (nutrient, 36, 20):
(history == Improved) && (time2 > 15 && time2 <=50) ? NormalDist (nutrient, 19, 7):
(history == Improved) && (time2 > 50) ? NormalDist (nutrient, 11.5, 3.5):
(history == Unimproved) && (time2 >= 0 && time2 <=15) ? NormalDist (nutrient, 11.5, 3.5):
(history == Unimproved) && (time2 > 15 && time2 <=50) ? NormalDist (nutrient, 11.5, 3.5):
(history == Unimproved) && (time2 > 50) ? NormalDist (nutrient, 11.5, 3.5):0

This equation describes the relationship between nutrient status and land-use history and time since cropping. A mean and standard deviation for available phosphorus for each state was estimated from the literature, which is translated into a probability of being in either a reference or enriched condition in Netica. These were calculated from data presented in papers by Standish *et al.* (2005) and Duncan *et al.* (2008). The availability of soil P declines over time at a highly variable rate (Standish *et al.* 2005). Phosphorus availability is likely to depend on factors such as soil type, frequency of fertilizer application and tree cover (Prober *et al.* 2002a; Standish *et al.* 2005; Duncan *et al.* 2008). As such, large bounds surround the estimates of mean available P (as reflected in the data). We assume that there is a chance of being in an enriched condition even if the site is unimproved (i.e. never cropped) and that this is equivalent to an improved site which has not been cropped for over 50 years.

Soil compaction

p (compaction | directseed, tubestock, disturbance, time) =
(directseed ==yes || disturbance == yes|| tubestock == yes) ? NormalDist (compaction, 0, 0.5):
(time > 30) ? NormalDist (compaction, 1.3, 0.5):
(time >3 && time <=30) ? NormalDist (compaction, 2, 1):
(time >=0 && time <=3) ? NormalDist (compaction, 5, 1.8): 0

This equation describes the relationship between soil compaction and time since grazing (time) and the application of the following management interventions: direct seeding, tube-stock and/or soil disturbance. It is assumed that the application of any of the management interventions completely ameliorates soil compaction by disturbing the soil. The mean and standard deviation for the relationship between time since grazing and compaction is based on a paper by Bassett *et al.* (2005). The compaction data came from records collected over a 30 year period from a reserve in New Zealand from which stock had been removed. As mentioned in Table 2, soil compaction declined rapidly in the initial years following stock removal but compaction varied substantially until around 30 years (Bassett *et al.* 2005). As such, it was assumed that there is a 50:50 chance of having compacted soil in the 'mid state' (3–30 years since grazing). Whilst there are reports that eucalypt seedling recruitment is negatively correlated with soil compaction (Spooner *et al.* 2002), the general paucity of Australian data needs to be addressed in order to determine whether soil compaction is an issue for the recruitment/survival of eucalypt seedlings.

Seed availability

```
p (seed | DS, mature_trees) =
(DS ==yes) ? 1.0:
(DS ==no) ? ( (1/(1+ (exp(-(2.35-(0.73*mature_trees))))): 0
```

This equation describes the availability of soil stored seed in relation to distance from the regeneration zone (mature_trees) and the implementation of direct seeding at a site. This binary node is expressed in terms of a probability of seed being present or absent. The assumption was made that if direct seeding is implemented, there will be seed present (i.e. probability of 1) regardless of the distance from the regeneration zone. If direct seeding is not implemented, seed availability is solely a function of distance from mature trees and is described from the work by Dorrough and Moxham (2005). They model the likelihood of seedling establishment with distance from mature trees under a number of different land-use scenarios. It has been found that seed rain varies annually and for different species, which is likely to be a function of climatic conditions (Morris *et al. in prep.*) but at this stage these factors are not incorporated into the model. For the equation, we assumed the response variable (seedling establishment) used by Dorrough and Moxham (2005) was equivalent to seed availability and used their model for seedling establishment in an ungrazed and uncultivated setting (where weed cover was held constant and the climatic conditions were estimated for the Violet Town region).

Weed competition

```
p (weed | control, nutrient, disturbance) =
(nutrient <=15) && (control == none) && (disturbance == no) ? NormalDist (weed, 24, 28):
(nutrient >=15) && (control == none) && (disturbance == no) ? NormalDist (weed, 84, 16):
(nutrient <=15) && (control == localised) && (disturbance == no) ? NormalDist (weed, 24, 28):
(nutrient >=15) && (control == localised) && (disturbance == no) ? NormalDist (weed, 84, 16):

(nutrient <=15) && (control == broadscale) && (disturbance == no) ? NormalDist (weed, 2, 2.3):
(nutrient >=15) && (control == broadscale) && (disturbance == no) ? NormalDist (weed, 7, 1.3):
(nutrient <=15) && (control == none) && (disturbance == yes) ? NormalDist (weed, 8, 9):
(nutrient >=15) && (control == none) && (disturbance == yes) ? NormalDist (weed, 28, 5):
(nutrient <=15) && (control == localised) && (disturbance == yes) ? NormalDist (weed, 8, 9):
(nutrient >=15) && (control == localised) && (disturbance == yes) ? NormalDist (weed, 28, 5):

(nutrient <=15) && (control == broadscale) && (disturbance == yes) ? NormalDist (weed, 1.2, 1.4):
(nutrient >=15) && (control == broadscale) && (disturbance == yes) ? NormalDist (weed, 4.2, 0.8): 0
```

This node describes the relationship between the child node weed cover (weed) and its parents: weed control (control), nutrient status (nutrient) and soil disturbance (disturbance). It is difficult to parameterise this node using studies from the literature, as there are few studies that examine the relationship between all variables. To describe a starting distribution of values that describe weed cover under reference and enriched conditions (i.e. no management intervention), we refer to a paper by Prober *et al.* (2002b). A mean and standard deviation for weed cover at sites under enriched conditions (> 15 ppm Colwell P, converted from Olsen P) and reference conditions (< 15 ppm Colwell P) were calculated. To determine the effect of management interventions we refer to a paper by Cole *et al.* (2005) which describes the effect of various weed control efforts in degraded Eucalypt woodlands in New South Wales. They examined the effect of various weed treatments, combined with soil disturbance (and including a control), on the cover of annual grasses over a 400 day period. The weed treatments used in their study constituted 'broad-scale' weed treatment according to the definition of states in this model (Table 4). The study by Cole *et al.* (2005) illustrated a three-fold reduction in annual grass cover if soil was disturbed only, a twelve-fold reduction if broad-scale herbicide was applied, and a twenty-fold reduction if soil was disturbed and herbicide applied (in 'lower landscape' positions). We applied these effects to the range of values (i.e. no management intervention) obtained from the Prober *et al.* (2002b) paper to produce the equation. It is assumed that 'localised' weed control is not effective in reducing the cover of annual grasses.

Grazing pressure

p (grazing | fence, density, pests, productivity) =

```
(fence == Stock_rabbits_hares) && (pests == Roos_rabbits) && (productivity == High) ? NormalDist (grazing, 0, 0.05):
(fence == Stock_rabbits_hares) &&( pests == Roos_rabbits) && (productivity == Low) ? NormalDist (grazing, 0, 0.05):

(fence == Stock_rabbits_hares) && (pests == Rabbits) && (productivity == High) ? NormalDist (grazing, 0.1, 0.05):
(fence == Stock_rabbits_hares) && (pests == Rabbits) && (productivity == Low) ? NormalDist (grazing, 0.1, 0.1):

(fence == Stock_rabbits_hares) && (pests == No) && (productivity == High) ? NormalDist (grazing, 0.2, 0.1):
(fence == Stock_rabbits_hares ) && (pests == No) && (productivity == Low) ? NormalDist (grazing, 0.3, 0.1):

(fence == Stock) && (pests == Roos_rabbits) && (productivity == High) ? NormalDist (grazing, 0, 0.1):
(fence == Stock) && (pests == Roos_rabbits) && (productivity == Low) ? NormalDist (grazing, 0, 0.1):

(fence == Stock) && (pests == Rabbits) && (productivity == High) ? NormalDist (grazing, 0.1, 0.1):
(fence == Stock) && (pests == Rabbits) && (productivity == Low) ? NormalDist (grazing, 0.2, 0.1):
(fence == Stock) && (pests == No) && (productivity == High) ? NormalDist (grazing, 0.2, 0.1):
(fence == Stock) && (pests == No) && (productivity == Low) ? NormalDist (grazing, 0.3, 0.1):

(fence == No) && (pests == Roos_rabbits) && (productivity == Low) && (density <= 5) ? NormalDist (grazing, 0.6, 0.1):
(fence == No) && (pests == Roos_rabbits) && (productivity == Low) && (density <= 8) ? NormalDist (grazing, 0.75, 0.1):
(fence == No) && (pests == Roos_rabbits) && (productivity == Low) && (density <= 12) ? NormalDist (grazing, 0.9, 0.05):

(fence == No) && (pests == Roos_rabbits) && (productivity == High) && (density <= 5) ? NormalDist (grazing, 0.4, 0.1):
(fence == No) && (pests == Roos_rabbits) && (productivity == High) && (density <= 8) ? NormalDist (grazing, 0.5, 0.1):
(fence == No) && (pests == Roos_rabbits) && (productivity == High) && (density <= 12) ? NormalDist (grazing, 0.6, 0.1):

(fence == No) && (pests == Rabbits) && (productivity == Low) && (density <= 5) ? NormalDist (grazing, 0.7, 0.1):
(fence == No) && (pests == Rabbits) && (productivity == Low) && (density <= 8) ? NormalDist (grazing, 0.8, 0.1):
(fence == No) && (pests == Rabbits) && (productivity == Low) && (density <= 12) ? NormalDist (grazing, 0.95, 0.05):

(fence == No) && (pests == Rabbits) && (productivity == High) && (density <= 5) ? NormalDist (grazing, 0.5, 0.1):
(fence == No) && (pests == Rabbits) && (productivity == High) && (density <= 8) ? NormalDist (grazing, 0.6, 0.1):
(fence == No) && (pests == Rabbits) && (productivity == High) && (density <= 12) ? NormalDist (grazing, 0.7, 0.1):

(fence == No) && (pests == No) && (productivity == Low) && (density <= 5) ? NormalDist (grazing, 0.8, 0.1):
(fence == No) && (pests == No) && (productivity == Low) && (density <= 8) ? NormalDist (grazing, 0.9, 0.1):
(fence == No) && (pests == No) && (productivity == Low) && (density <= 12) ? NormalDist (grazing, 1, 0.05):

(fence == No) && (pests == No) && (productivity == High) && (density <= 5) ? NormalDist (grazing, 0.6, 0.1):
(fence == No) && (pests == No) && (productivity == High) && (density <= 8) ? NormalDist (grazing, 0.7, 0.1):
(fence == No) && (pests == No) && (productivity == High) && (density <= 12) ? NormalDist (grazing, 0.8, 0.1):0
```

This node illustrates the effect of grazing exclusion (fence), stock density (SD), pest control (pests) and landscape productivity (productivity) in relation to grazing pressure. Tables 3 and 4 give a full description of the states involved in this equation. The distributions used in the following equation are determined largely by best guess and dependent on several assumptions. First, we assume that fencing for 'stock, rabbits and hares' results in negligible grazing pressure, unless pest control is not undertaken. Second, fencing for 'stock' will generally mean grazing pressure is very low and restricted to rabbits and kangaroos ('Rabbits_roos'), though with no pest control and a high density of rabbits/kangaroos it is possible to achieve a 'low' grazing pressure. Third, a 'low' stock density under 'high' productivity conditions will always result in a 'low' grazing pressure (which is then variable with regard to pest control). In contrast, a 'low' stock density under 'low' productivity conditions will result in a 'low' to 'high' grazing pressure depending on the application of pest control. Last, 'high' stock density will always result in a 'high' grazing pressure but within this state there is variation in relation to landscape productivity and pest control.

Seedling establishment

The CPT for seedling establishment in relation to weed competition, tube-stock, soil compaction, seed availability, short-term rainfall and grazing pressure is based on findings from a seedling regeneration model published by Vesk and Dorrough (2006). In this paper they modelled the natural recruitment of eucalypt seedlings using a rule- and stage- based model. The model combined existing knowledge to try and improve the understanding of how best to achieve natural regeneration across the landscape. Not all variables and states used within the regeneration model matched those within this model. Table 5 describes the variables and states used in the seedling regeneration model (Vesk and Dorrough 2006) and how they were used to match those in the BBN.

The seedling regeneration model was run for each combination of states and each combination was simulated 100 times for a five-year period. The results were modified to include the impacts of compaction and tube-stock on seedling establishment. A scenario that considered tube-stock plantings was tested by running the model with a high level of small (<0.5 m) seedlings present at the first time step (as in Dorrough *et al.* 2008a). As mentioned previously, the impact of compaction on eucalypt seedling establishment is uncertain, so for the time being it is estimated that a compacted soil reduces the probability of seedling establishment by 0.8 (i.e. of the non-compacted result). If tube-stock has been planted, soil compaction has been ameliorated and is not considered in the CPT.

There is uncertainty surrounding the success of restoration projects when using direct seeding methods compared to tube-stock (Schirmer and Field 2000; Graham 2006) but in the model the likelihood that seedlings will establish is highest using tube-stock compared to direct seeding. Tube-stock provides an immediate result, compared to the time lag expected with direct seeding methods, but whether one method is more successful than the other is open to debate. It is expected that this uncertainty will be reduced through field trials and monitoring, so the model can be updated as knowledge accrues.

There were a number of growth stages modelled in the natural regeneration model but for the purposes of the BBN only the probabilities for establishment of small seedlings (under 50 cm height) were recorded. The CPT Table was filled out directly using the results from the regeneration model, and is presented below.

Sapling escape

The node woodland establishment is dependent on

Table 5. The variables and states included in the seedling regeneration model (Vesk and Dorrough 2006) and how they relate to the variables and states in the BBN.

Variable	Summary and states	Equivalent BBN variable
Seed supply	Seed production of eucalypts. Discrete states set at low, medium and high.	Seed availability. The results for the low and medium seed production states are used to reflect the two states (absent/present) within the BBN.
Winter rain	Rainfall April–September. Dry Medium and Wet	These factors are combined in the BBN to represent short-term rainfall. The state combination of Wet_W-Wet_S is used to represent a favourable rainfall period, which must occur once in the five-year period.
Summer rain	Rainfall October–March. Dry, Medium and Wet	
Grazing	Intensity of grazing, as either none-light, or heavy.	Grazing Pressure, which has three states. It is assumed the effect of grazing on seedling establishment is linear, so the probabilities for the 'mid' state are calculated as halfway between the light and heavy states.
Pasture growth	Describes productivity, or pasture growth. Described as high and low productivity to reflect cultivated introduced annual pastures and native perennial pastures respectively.	This variable is equivalent to the weed competition node in the BBN, which also has two states (low/high).
Fire	Wildfire. Yes or No.	No fire node. In the simulations the probability of fire was held constant at 0.
Biomass cut	Removal of biomass/competition	No equivalent node that directly affects seedling establishment. Held constant in the simulation.
Seedling establishment	Seedlings are classified into a number of size classes, and recorded as either present or absent in a given year.	Represents the number of small seedlings (< 50 cm) found as a proportion of the length of the model run (in years)
Sapling escape	Saplings (> 1 m) are present or absent in a given year.	Represents the number of saplings (> 1 m) found as a proportion of the length of the model run (in years)

seedling establishment, grazing pressure and post-establishment rainfall. It is assumed that woodland establishment fails (i.e. probability of failure = 1) in the event of failed seedling establishment. For the other state combinations, the CPT was again filled using the findings from the seedling regeneration model published by Vesk and Dorrough (2006). As we are interested in observing saplings within 10 years of management intervention, the model was run for a period of seven years (i.e. considers seedling establishment after three years), with a high density of seedlings present at the initial time step. The different state combinations for grazing pressure and rainfall were tested (Table 5), whilst all other variables in the model were held constant. In this case, a favourable rainfall period was considered if it occurred in either summer or winter and at least three of these periods were required over the 5–7 year monitoring period.

Parentless nodes (Controlling factors and Management interventions)

Lastly, nodes without parents (e.g. Land-use history) were assigned equal probabilities across states to indicate there is no prior knowledge used to inform these nodes. The exception may be the nodes describing short and medium-term rainfall, as the likelihood of being in a particular state can be calculated using weather forecasts for a particular region.

Conditional Probability Table for seedling establishment

						Seeding establishment	
Tube-stock	**Seed availability**	**Rainfall**	**Grazing pressure**	**Weed competition**	**Soil compaction**	**LIKELY**	**UNLIKELY**
No	Absent	Low	Rabbits_roos	Low	No	0.27	0.73
No	Absent	Low	Rabbits_roos	Low	Yes	0.22	0.78
No	Absent	Low	Rabbits_roos	High	No	0.10	0.90
No	Absent	Low	Rabbits_roos	High	Yes	0.08	0.92
No	Absent	Low	Low	Low	No	0.14	0.86
No	Absent	Low	Low	Low	Yes	0.11	0.89
No	Absent	Low	Low	High	No	0.05	0.95
No	Absent	Low	Low	High	Yes	0.04	0.96
No	Absent	Low	High	Low	No	0.00	1.00
No	Absent	Low	High	Low	Yes	0.00	1.00
No	Absent	Low	High	High	No	0.00	1.00
No	Absent	Low	High	High	Yes	0.00	1.00
No	Absent	High	Rabbits_roos	Low	No	0.55	0.45
No	Absent	High	Rabbits_roos	Low	Yes	0.44	0.56
No	Absent	High	Rabbits_roos	High	No	0.21	0.79
No	Absent	High	Rabbits_roos	High	Yes	0.17	0.83
No	Absent	High	Low	Low	No	0.32	0.68
No	Absent	High	Low	Low	Yes	0.26	0.74
No	Absent	High	Low	High	No	0.16	0.84
No	Absent	High	Low	High	Yes	0.13	0.87
No	Absent	High	High	Low	No	0.10	0.90
No	Absent	High	High	Low	Yes	0.08	0.92
No	Absent	High	High	High	No	0.10	0.90
No	Absent	High	High	High	Yes	0.08	0.92
No	Present	Low	Rabbits_roos	Low	No	0.73	0.27
No	Present	Low	Rabbits_roos	Low	Yes	0.58	0.42
No	Present	Low	Rabbits_roos	High	No	0.33	0.67
No	Present	Low	Rabbits_roos	High	Yes	0.27	0.73
No	Present	Low	Low	Low	No	0.45	0.55
No	Present	Low	Low	Low	Yes	0.36	0.64
No	Present	Low	Low	High	No	0.25	0.75
No	Present	Low	Low	High	Yes	0.20	0.80
No	Present	Low	High	Low	No	0.17	0.83

No	Present	Low	High	Low	Yes	0.14	0.86
No	Present	Low	High	High	No	0.17	0.83
No	Present	Low	High	High	Yes	0.14	0.86
No	Present	High	Rabbits_roos	Low	No	0.86	0.14
No	Present	High	Rabbits_roos	Low	Yes	0.69	0.31
No	Present	High	Rabbits_roos	High	No	0.50	0.50
No	Present	High	Rabbits_roos	High	Yes	0.40	0.60
No	Present	High	Low	Low	No	0.66	0.34
No	Present	High	Low	Low	Yes	0.52	0.48
No	Present	High	Low	High	No	0.47	0.53
No	Present	High	Low	High	Yes	0.38	0.62
No	Present	High	High	Low	No	0.45	0.55
No	Present	High	High	Low	Yes	0.36	0.64
No	Present	High	High	High	No	0.44	0.56
No	Present	High	High	High	Yes	0.35	0.65
Yes	Absent	Low	Rabbits_roos	Low	No	0.78	0.22
Yes	Absent	Low	Rabbits_roos	Low	Yes	0.78	0.22
Yes	Absent	Low	Rabbits_roos	High	No	0.82	0.18
Yes	Absent	Low	Rabbits_roos	High	Yes	0.82	0.18
Yes	Absent	Low	Low	Low	No	0.64	0.36
Yes	Absent	Low	Low	Low	Yes	0.64	0.36
Yes	Absent	Low	Low	High	No	0.66	0.34
Yes	Absent	Low	Low	High	Yes	0.66	0.34
Yes	Absent	Low	High	Low	No	0.50	0.50
Yes	Absent	Low	High	Low	Yes	0.50	0.50
Yes	Absent	Low	High	High	No	0.51	0.49
Yes	Absent	Low	High	High	Yes	0.51	0.49
Yes	Absent	High	Rabbits_roos	Low	No	0.87	0.13
Yes	Absent	High	Rabbits_roos	Low	Yes	0.87	0.13
Yes	Absent	High	Rabbits_roos	High	No	0.87	0.13
Yes	Absent	High	Rabbits_roos	High	Yes	0.87	0.13
Yes	Absent	High	Low	Low	No	0.75	0.25
Yes	Absent	High	Low	Low	Yes	0.75	0.25
Yes	Absent	High	Low	High	No	0.74	0.26
Yes	Absent	High	Low	High	Yes	0.74	0.26
Yes	Absent	High	High	Low	No	0.62	0.38
Yes	Absent	High	High	Low	Yes	0.62	0.38
Yes	Absent	High	High	High	No	0.61	0.39
Yes	Absent	High	High	High	Yes	0.61	0.39
Yes	Present	Low	Rabbits_roos	Low	No	0.97	0.03
Yes	Present	Low	Rabbits_roos	Low	Yes	0.97	0.03
Yes	Present	Low	Rabbits_roos	High	No	0.93	0.07
Yes	Present	Low	Rabbits_roos	High	Yes	0.93	0.07
Yes	Present	Low	Low	Low	No	0.82	0.18
Yes	Present	Low	Low	Low	Yes	0.82	0.18
Yes	Present	Low	Low	High	No	0.79	0.21
Yes	Present	Low	Low	High	Yes	0.79	0.21
Yes	Present	Low	High	Low	No	0.67	0.33
Yes	Present	Low	High	Low	Yes	0.67	0.33
Yes	Present	Low	High	High	No	0.65	0.35

Yes	Present	Low	High	High	Yes	0.65	0.35
Yes	Present	High	Rabbits_roos	Low	No	0.99	0.01
Yes	Present	High	Rabbits_roos	Low	Yes	0.99	0.01
Yes	Present	High	Rabbits_roos	High	No	0.95	0.05
Yes	Present	High	Rabbits_roos	High	Yes	0.95	0.05
Yes	Present	High	Low	Low	No	0.92	0.08
Yes	Present	High	Low	Low	Yes	0.92	0.08
Yes	Present	High	Low	High	No	0.90	0.10
Yes	Present	High	Low	High	Yes	0.90	0.10
Yes	Present	High	High	Low	No	0.85	0.15
Yes	Present	High	High	Low	Yes	0.85	0.15
Yes	Present	High	High	High	No	0.85	0.15
Yes	Present	High	High	High	Yes	0.85	0.15

Conditional Probability Table for sapling escape

			Sapling escape	
Seedling establishment	**Grazing pressure**	**Rainfall**	**LIKELY**	**UNLIKELY**
Unlikely	Rabbits_roos	Low	0.00	1.00
Unlikely	Rabbits_roos	High	0.00	1.00
Unlikely	Low	Low	0.00	1.00
Unlikely	Low	High	0.00	1.00
Unlikely	High	Low	0.00	1.00
Unlikely	High	High	0.00	1.00
Likely	Rabbits_roos	Low	0.33	0.67
Likely	Rabbits_roos	High	0.46	0.54
Likely	Low	Low	0.16	0.84
Likely	Low	High	0.23	0.77
Likely	High	Low	0.00	1.00
Likely	High	High	0.00	1.00