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Using a State-and-Transition Approach to Manage Endangered *Eucalyptus albens* (White Box) Woodlands

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Abstract *Eucalyptus albens* (White Box) woodlands are among the most poorly conserved and threatened communities in Australia. Remnants are under further threat from stock grazing, deteriorating soil conditions, weed invasion, and salinity. There is an urgent need to restore degraded White Box and other woodland ecosystems to improve landscape function. However, there is still a poor understanding of the ecology of degraded woodland ecosystems in fragmented agricultural landscapes, and consequently a lack of precise scientific guidelines to manage these ecosystems in a conservation context. State and Transition Models (STMs) have received a great deal of attention, mainly in rangeland applications, as a suitable framework for understanding the ecology of complex ecosystems and to guide management. We have developed a STM for endangered White Box woodlands and discuss the merits of using this approach for land managers of other endangered ecosystems. An STM approach provides a greater understanding of the range of states, transitions, and thresholds possible in an ecosystem, and provides a summary of processes driving the system. Importantly, our proposed STM could be used to clarify the level of ‘‘intactness’’ of degraded White Box woodland sites, and provide the impetus to manage different states in complementary ways, rather than attempting to restore ecosystems to one pristine stable state. We suggest that this approach has considerable potential to integrate researcher and land manager knowledge, focus future experimental studies, and ultimately serve as a decision support tool in setting realistic and achievable conservation and restoration goals.

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Introduction

Increasing land degradation has led to a growing urgency among farmers, land managers, and researchers to develop better coordinated approaches for restoring degraded woodland ecosystems in Australia (Yates and Hobbs 1997a, 1997b; Yates and others 2000). In most temperate regions, only scattered elements of original ecosystems remain in predominantly cleared agricultural landscapes (Prober and Thiele 1993; Sivertsen 1993). So great has been the effect of agricultural land use on temperate woodland ecosystems in southeastern Australia that we are often at a loss as to how to restore these ecosystems (Prober and Thiele 2005), and only a minimal understanding of how they would have developed without such impacts (Fry and Main 1993). Remnant woodlands are often highly degraded with little or no regeneration of tree and shrub species, compacted, acidic, or saline soils, and increasing dominance of exotic species (e.g., Adamson and Fox 1982; Hobbs and Hopkins 1990; Benson 1991; Yates and

Hobbs 1997a). As a result, there are few unmodified remnants, and *Eucalyptus albens* (White Box) woodlands are listed as endangered ecological communities.

Unfortunately, we still have a poor understanding of the ecology of woodland remnants (Prober 1996), and thus lack precise scientific guidelines to manage and restore woodland remnants (Yates and Hobbs 1997b). As a result, restoration ecology has progressed on an ad-hoc, site- and situation-specific basis with little development of general theory or principles that would allow the transfer of methodologies from one situation to another (Hobbs and Norton 1996; Yates and Hobbs 1997a). For example, many federal and state government projects provide incentives to fence remnants to control grazing by stock, or to revegetate with native species; however, studies have shown that recovery is not assured and sites remain in a steady degraded "state" (Spooner and others 2002). The failure of many fenced remnants to spontaneously recover suggests that "ecological thresholds" have been passed, and changes are irreversible unless further active management is undertaken (Yates and others 2000; Allcock 2002b). Development of appropriate management and restoration measures clearly demands a better ecological understanding of how far we can restore degraded woodland ecosystems to a self-sustaining state, and what techniques are appropriate (Fry and Main 1993; Allcock and others 1999).

To date, traditional climax theory (Clements 1928) has been the basis for management expectations that degraded woodland ecosystems will return to their previous state after removal of degrading disturbances, e.g., removing grazing by domestic stock (Laycock 1991; Yates and Hobbs 1997b). Climax theory views transitions in a vegetation community as linear and predictable, and disturbances are seen as discrete events, followed by secondary succession leading back to the original, stable climax community (Clements 1928; Westoby and others 1989a; Whalley 1994). However, in many ecosystems, it is generally accepted that disturbances produce multiple successional paths (e.g., Moore 1953; May 1977; Noble and Slatyer 1980; Westoby and others 1989a, 1989b, Dublin and others 1990; Laycock 1991; George and others 1992; Packard 2000).

The State and Transition Model approach (STM), based on nonequilibrium ecology (e.g., Krebs 1999; Briske and others 2003), has been proposed to account better for widely observed nonlinear plant community dynamics (e.g., Bestelmeyer and others 2004). STMs have been primarily applied in rangeland management (Westoby and others 1989a, 1989b; Whalley 1994; Grice and MacLeod 1994; Stringham and others 2003); however, it has been recently suggested that they are equally useful in a conservation management context, particularly for endangered ecosystems that are fragmented and exist in various levels of degradation (Thiele and Prober 2000; Prober and others 2001), as is the case for many woodland ecosystems in agricultural landscapes of Australia (e.g., Huntsinger and Bartolome 1992; Plant and Vayssieres 2000; McIntosh and others 2003; Allcock and Hik 2004).

The development of STMs has important implications for management of endangered ecosystems. In particular, it highlights (1) that ecosystems are rarely pristine, and therefore criteria other than "naturalness" are required in the selection of conservation reserves (Oliver and others 2002); (2) that management goals need to recognize and incorporate a wide variety of ecosystem conditions, and attempt to manage different ecosystem conditions or "states" in complementary ways, rather than by attempting to manage all areas to one stable state (Prober and Thiele 2005); (3) key interactions, threatening processes, or barriers to management and restoration activities are more clearly identified (Yates and Hobbs 1997b; Yates and others 2000); (4) that interventions should be state specific, because different ecosystems contain different biota and potential barriers to restoration (Lunt and Spooner 2005), and (5) their effectiveness as a tool to communicate the notion of thresholds to land managers (Bestelmeyer and others 2004). By clearly documenting the wide range of ecological transformations that have occurred due to human modification of ecosystems, more realistic goals can be set for future management and research activities.

In this article, we have summarized existing knowledge of temperate woodland ecosystems in Australia, and developed a proposed STM for vegetation change in *Eucalyptus albens* (White Box) woodlands in southeastern Australia. The aim is to provide a framework, based on a STM approach, for more effective management and restoration of degraded White Box woodlands, and to provide a sound conceptual framework for future research activity. A key issue to successful restoration of endangered ecosystems is in the setting of clear restoration goals, and comparison to suitable reference conditions, which will also be discussed in a STM context. We suggest that this approach may be of considerable benefit for conservation of depleted or degraded communities elsewhere.

State and Transition Models

The STM illustrates major processes operating in ecosystems, by describing changes in vegetation in terms of structure, presence and absence of species, and changes in abiotic conditions (Hobbs and Norton 1996). The STM is a conceptual construct to explain successional pathways, by combining various mechanisms of change, and specifying the relationship among these and the various ''states'' along the pathways presented (Pickett and others 1987). The STM embraces the concept of multiple stable vegetative ''states,'' which recognizes that disturbances such as stock grazing can cause change in a community from one state to another (Whalley 1994). Reversibility between vegetative ''states'' depends upon the survival or re-establishment of particular species within the community (which may be a matter of chance), and the reversibility of changes in environmental factors, e.g., soil properties or stocking rates (Adamson and Fox 1982; Whalley 1994; Hobbs and Norton 1996). Such reversibility may not occur, even after the removal of the disturbance factor, when vital components of the original system have been lost or changed (Dublin and others 1990; Yates and Hobbs 1997a, 1997b; Packard 2000). The STM recognizes the following concepts:

1. That alternative ''states'' are possible in any particular location, and a set of discrete ''transitions'' can occur between states;
2. That ''thresholds'' exist, where certain environmental factor(s) are essential to natural states, and exist between varying degraded levels of the natural state;
3. If an ecosystem in a particular degraded state has the degrading influence removed, but has not crossed a threshold, transition back to the original state may occur; and
4. If an ecosystem in a particular degraded state has the degrading influence removed, but has crossed a ''threshold,'' transition back to the original state will not occur without management intervention.

''States'' are vegetation complexes that remain the same or change only slowly over a management time–horizon, and are the product of interactions between a number of environmental (e.g., climate, soils) and management factors (e.g., grazing) (Huntsinger and Bartolome 1992; Bellamy and Brown 1994; Yates and Hobbs 1997b). A state is an abstraction encompassing a certain amount of variation in space and time (Westoby and others 1989a). Importantly in a STM, states are user-defined. For example, one user may define alternate states in terms of structure, whereas another may use a full floristic approach or the presence or absence of rare or endangered species (Whalley 1994).

''Transitions'' are pathways between states, and may be triggered by natural events (e.g., drought) or by management practices (e.g., grazing), or by a combination of the two (Westoby and others 1989a; George and others 1992). Transitions may occur swiftly or over a long period of time, and may be irreversible (Huntsinger and Bartolome 1992; Yates and Hobbs 1997b). The factors driving transitions between states, and shaping the characteristics of states, are identified and catalogued. STMs therefore assist in the testing of hypotheses about the various transitions, either natural or anthropogenic (Westoby and others 1989a, 1989b, George and others 1992; Bestelmeyer and others 2003, 2004).

''Thresholds'' are asymmetric boundaries in composition or function between ecosystem states. A threshold is indicated when a transition between vegetation states cannot be reversed by simply removing or reversing the disturbance that caused the initial shift (Brown 1994; Stringham and others 2003). Once a threshold is passed, most ecosystems cannot pass back without some form of intervention or management input (Friedel 1991; Filet 1994; Hobbs and Norton 1996). For example, reconstitution of seed banks, replanting of extinct species, or amelioration of soil conditions may all be required for remnant woodland sites that have passed such thresholds (George and others 1992; Board 2002). Thresholds, such as depleted seedbanks, may explain the lack of regeneration of shrub species in *Eucalyptus melliodora* (Yellow Box) and *E. microcarpa* (Grey Box) woodlands after grazing exclosure (Spooner and others 2002).

Westoby and others (1989a) suggested five mechanisms that could lead to thresholds in grazing systems: (i) demographic inertia (rare or sporadic recruitment events), (ii) grazing catastrophe (population collapse), (iii) competition priority or space pre-emption (e.g., ability of adult plants to exclude seedlings of other species), (iv) positive feedback loops (e.g., fire promotion by fire-tolerant species), and (v) soil changes (e.g., plant-soil feedbacks). In addition, factors related to the species pool such as local extinction, introduction or invasion of new species, and dispersal limitation could create effective boundaries to restoration, especially in fragmented ecosystems.

A STM approach would be advantageous in the management of degraded White Box or other woodland ecosystems, by providing a better understanding of potential thresholds between vegetation states that processes such as local extinctions, weed invasions, or disruption of natural disturbance regimes may have created. In particular, it permits more constructive analysis of the effects of natural disturbance and human activity in determining vegetation structure, and pathways to restoration (e.g., Huntsinger and Bartolome 1992; Whalley 1994; Hobbs and Norton 1996).

Why Use a STM Approach?

The major advantages to using STMs to describe an ecosystem are to facilitate greater synthesis and integration of land manager "expert" knowledge and research findings; to highlight information deficiencies; and to provide a sound scientific basis for ongoing management (e.g., Huntsinger and Bartolome 1992; Filet 1994; Taylor and others 1994; McIntosh and others 2003). Development of a STM with the understanding of all stakeholders provides a logical structure to test the validity of opinion and anecdotal evidence (Stockwell and others 1994). STMs are a versatile and efficient way to organize knowledge of a system, allowing for adaptive management (Prober and Thiele 1995), because it is possible to refine the model as more information is obtained. In fact, this was the original intention of STMs (Westoby and others 1989b). It is also possible to incorporate both qualitative and quantitative information into the framework.

Developing STMs need not be complex or costly. For example, in studies of grazing exclusion trials in grasslands in Patagonia, transitions and thresholds were simply explored using Principal Components Analysis and regression techniques (Gabriel and others 1998). In studies of soil and associated understorey composition changes in Australian woodlands, a STM was developed and regression and other standard statistical techniques were used to compare attributes between ecosystem states (Prober and others 2002a, 2002b). STMs are particularly useful for land managers to describe changes to ecosystems based on actual observations. For example, in a social science study of grassland changes in South Africa, a simple STM was utilized to highlight a range of social and institutional factors influencing grassland dynamics (Kepe and Scoones 1999). These studies have highlighted some of the major advantages of STMs in communication of research findings and development of hypotheses for testing.

A typical criticism of STMs is that they often lack quantifiable data. Indeed, without such data a STM is just a subjective interpretation of a system (Grice and MacLeod 1994; Allen-Diaz and Bartolome 1998). This may be of no concern in terms of communication, but it does concern some ecologists who wish to connect theory and data. For example, Grice and MacLeod (1994) warned of the "seductive" nature of STMs and their inherent simplicity. Westoby and others (1989) also noted that details of an ecosystem can be lost depending on the number of states and transitions recognized. More importantly, there are few long-term studies that can directly confirm the hypothesis that multiple stable states can exist in an ecosystem (Dublin and others 1990; Petraitis and Latham 1999).

However, the view that ecosystems can possess multiple stable states is supported both by theoretical mathematical models and a large body of empirical observations (e.g., May 1977, Noble and Slatyer 1980; Scheffer and Carpenter 2003). In addition, it is quite possible to develop STMs from both empirical and observational data, by basing states on classification or ordination using a large number of sample points within identified vegetation types (Bestelmeyer and others 2004). This approach may even include an investigation of spatial patterning where the history of disturbance is known (e.g., Bork and others 1997; Plant and others 1999). A combination of empirical and qualitative information can allow STMs to be tested explicitly (e.g., Plant and others 1999).

A Proposed STM for White Box Woodlands

Changes in botanical composition and structure of Australian temperate woodland ecosystems as a result of past European management practices (e.g., grazing by domestic stock) have been well documented by various authors (e.g., Moore 1973; Adamson and Fox 1982; Prober and Thiele 1993, 1995, Yates and Hobbs 1997a). In general, grazing pressure has reduced the abundance of native perennial grasses, particularly palatable species, throughout much of the Australian wheat-sheep belt (e.g., Wilson 1990; Benson 1991). A common trend is a decrease in the diversity and abundance of native perennial forbs and grasses, and an increase in exotic annuals and ephemerals (Moore 1953; Adamson and Fox 1982; Lodge and Whalley 1989; Wilson 1990; Lunt 1991; Sivertsen 1993; McIntyre and Lavorel 1994; Pettit and others 1995; Lunt and Morgan 1999).

We present a STM that was developed for *Eucalyptus albens* (White Box) woodlands at Burrendong Dam NSW, based on literature review, historical records, and observations from experienced land managers (Allcock 2002b). We have endeavored to develop a STM for White Box woodlands that is consistent with research findings and land managers' perceptions of the ecosystem (Figures 1 and 2). The literature used to determine the various states, transitions, and thresholds in our proposed STM is listed in Table 1, and

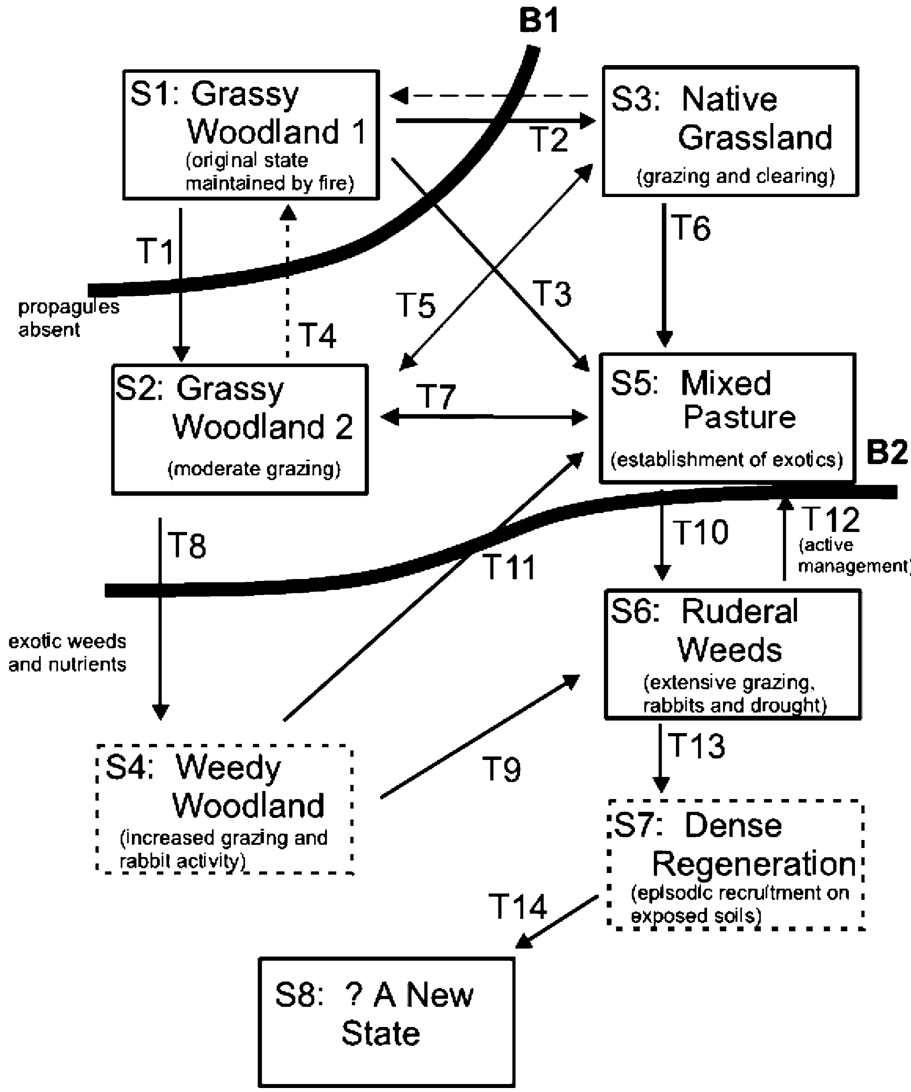

Fig. 1 A state and transition model for vegetation change in *Eucalyptus albens* (White Box) woodlands, Burrendong Dam study site, NSW (Allcock and others 1999; Allcock 2002b). Boxes represent vegetation states; arrows indicate transitions. Dashed boxes are transient states that will move to another state without perturbation. Heavy curved lines indicate threshold conditions.

summarized below. Empirical tests of the thresholds identified in the model are discussed in more detail in Allcock (2002b).

In the proposed STM (Figures 1 and 2), the original White Box woodland community [S1] consists of *E. albens* with an understorey of perennial warm season grasses with scattered native forbs and occasional shrubs. Prior to heavy stock grazing, *Themeda australis* and *Poa sieberiana* were most likely the dominant species (Moore 1973; Prober and Thiele 1993). The introduction of domestic stock in the 1840s forced the original woodlands towards an understorey dominated by cool-season perennials such as *Austrodanthonia* and *Austrostipa* [S2]. Clearing to improve pasture and subsequent grazing changed much of the woodland to native grasslands [S3] (Colclough 1960; Moore 1973; Adamson and Fox 1982).

Cool-season–dominated woodlands [S2] were probably maintained by light to moderate stocking. However, a long history of grazing has resulted in the disappearance of palatable species and likely depletion of the seed bank (e.g., Lunt 1997; Lunt and Morgan 1999). *Themeda*, for example, is considered an ‘‘extinction prone’’ grass because of its susceptibility to grazing and inability to form long-term seed banks (O’Connor 1991). Interactions between drought and sustained grazing may also have led to a collapse of perennial grass populations (Adamson and Fox 1982; Wilson 1990). The loss of propagules of native species creates a threshold [B1] preventing a return to initial vegetation composition [S1] from cool-season woodlands or grasslands.

Grazing and removal of overstorey trees results in cool-season native grasslands [S3]. These consist primarily of perennial grasses and native forbs, and could be maintained by light grazing. Reversion to [S2] would be possible, but only with tree seed input and adequate rainfall. Continued grazing and sub-

Fig. 2 Catalogue of states, transitions, and threshold boundaries for diagram in Figure 1.

States

S1: pristine woodland – White Box canopy and tall grass/forb understorey. Maintained by fire and light grazing, and perhaps competition for water.

S2: grazed woodland – White Box canopy and short grass understorey. Maintained by stock grazing.

S3: native grassland – canopy cleared; grassland of short native species. Maintained by stock grazing.

S4: weedy woodland – transient state. Canopy dying, not regenerating. Understorey of invasive weeds.

S5: mixed pasture – canopy cleared, sown pasture species, invasive species, and some less palatable native grasses.

S6: ruderal weeds – badly degraded by overgrazing, no perennial cover. Unpalatable weeds dominate.

S7: dense regeneration – transient state. Primarily *Callitris glaucophylla,* dense even aged stands.

S8: not yet observed at Burrendong. Outcome of aging and self-thinning in S7. Perhaps *C. glaucophylla* woodlot?

Transitions

T1: grazing of pristine woodland causes reduction or loss of grazing sensitive species and shift to dominance of short grasses.

T2: grazing and clearing removes trees and causes shift to dominance of short grasses; may be reversible early in transition (see T4).

T3: concurrent clearing, grazing, fertilization, and introduction of exotics move pristine woodland directly to mixed pasture.

T4: removal of grazing early in transition from S1 to S2 may permit recovery to S1, but T4 is very unlikely.

T5: recruitment of trees into native grassland, a rare event, or clearing of trees in native woodland.

T6: addition of fertilizer, sown pasture species, and invasive exotic species moves native grassland to mixed grassland.

T7: tree clearing, addition of fertilizer and pasture species, and invasion of exotic species move S2 to S5. Recruitment or planting of trees in S5 moves to S2 (rare).

T8: fertilization, stock camps, and invasion of noxious weeds move S2 to S4.

T9: tree death moves S4 to S6.

T10: continued heavy grazing, erosion, and invasion of noxious weeds moves S5 to S6.

T11: tree death moves S4 to S5.

T12: prompt management such as de-stocking and rabbit control (seen at Burrendong in 1960's) can return S6 to S5.

T13: management attempts to move from S6 to S5 can also result in transition to S7 if propagules available (seen at Burrendong)

T14: growth and self-thinning of S7 creates S8, a previously unrecorded state for woodlands in the Burrendong area.

Thresholds (Asymmetric boundaries)

B1: Grazing causes local extinction of sensitive species (e.g., kangaroo grass). Removalof grazing does not allow return to S1 because of extinction events and loss of propagules.

B2: Addition of nutrients (phosphate), introduction of pasture species, and invasion of exotic weeds alters understorey composition. Despite reduction of grazing, native plants can not compete with and eliminate exotic species, and return from S4 or S6 to S2 or S5 is prevented.

sequent invasion of exotic species causes a further shift towards an understorey dominated by grazing- and drought-tolerant native species (including *Bothriochloa macra* and *Chloris truncata*) and exotic species [S5] (Moore 1973). The presence of exotic species (mostly annuals) and changes in soil fertility could then create a second threshold [B2]. Nutrient enrichment, especially seeding of nitrogen-fixing species and addition of phosphorus fertilizers, likely stimulated growth of exotic annuals to a greater extent than native species (Allcock 2002a; Prober and others 2002a, 2002b). This would create a threshold by allowing exotic species to compete effectively with native perennial species and create nutrient-cycling feedbacks (Wedin 1999).

Continued heavy grazing, in conjunction with rabbit activity, results in degraded woodland patches mostly dominated by noxious weeds [S4]. In mixed pasture sites [S5], continued heavy grazing and rabbit activity leads to further loss of native species, resulting in patches dominated by exotic ruderal weeds [S6]. Because seedling recruitment of eucalypts such as *E. albens* is often low in sites with a non-native understorey (Curtis 1990; Cluff and Semple 1994; Windsor 1999; Spooner and others 2002), and trees in degraded sites often suffer from dieback (Curtis 1990; Landsberg and Wylie 1991), senescence and eventual death of mature trees will result in weedy woodlands declining to degraded or mixed pastures. Yates and Hobbs (1997a) have suggested that continued grazing

Table 1 Literature sources used in the construction of the state and transition model for *Eucalyptus albens* (White Box) woodlands (Figures 1 and 2), including the location and topic of each paper, and the components of the models to which each source was applied[a]

Source	Topic and region	Model
Adamson & Fox (1982)	Vegetation change since European settlement in Australia; causes of rapid vegetation change	B1, T1-T8, S1-S5
Beadle (1948)	The vegetation and pastures of western New South Wales with special reference to soil erosion	B1, B2, T1-T8, S1-S5
Benson (1991)	Vegetation change since European settlement; habitat loss in temperate woodlands	B1, T1-T8, S1-S5
Benson (1999)	Past and present vegetation of NSW, threats, and conservation plans	B1, T1-T8, S1-S5
Clayton-Greene & Ashton (1990)	Composition and dynamics of White Box and *Callitris* woodlands in southern NSW	S1-S2, T5
Colclough 1960	Vegetation change and land management at Burrendong Dam	S2-S7, T10, T12, T13
Hodgekinson & Cook (1995)	Perennial grass collapse under grazing in arid rangelands	B1, T1, T4
Lodge & Whalley (1989)	Native and natural pastures on the northern slopes and tablelands of New South Wales	B1, B2, T1-T8, S1-S5
Logan (1957a,b)	Vegetation change and land management at Burrendong Dam	S2-S7, T10, T12, T13
Lunt (1991)	Conservation and management of grasslands and grassy woodlands in southeastern Australia	B1, T1-T8, S1-S5
Lunt (1995)	Management effects and recommendations in grassy woodlands of southeastern Australia	B1, T1-T8, S1-S5
Moore (1953)	The vegetation of the southeastern Riverina, New South Wales. II. The disclimax communities	B1, B2, T1-T8, S1-S5
Moore (1973)	Composition and vegetation change with grazing in temperate grasslands and woodlands of eastern Australia	B1, B2, T1-T8, S1-S5
O'Connor (1991)	Extinction in perennial grasslands in Africa	B1, T1, T2, T4
Prober & Thiele (1993)	Conservation status of grassy White Box woodlands in NSW	B1, T1-T8, S1-S5
Prober & Thiele (1995)	Vegetation composition and land use of grassy White Box woodlands	B1, B2, T1-T8, S1-S5
Prober and others (2002a)	Soil-related restoration barriers in White Box woodlands	B2, S1-S6
Prober and others (2002b*)*	Determining ''reference conditions'' for White Box woodlands	S1, B1
Reed (1991)	History of woodland change and conservation in NSW	S1-S6, T1-T11, B1, B2
Windsor (1999)	Regeneration of White and Yellow Box (*E. melliodora*) in central west NSW	B2, T9, T11, S4
Yates and Hobbs (1997a,b)	Use of S&T models for understanding vegetation change in Salmon Gum woodlands in WA; threatening processes in Australian temperate woodlands	B1, B2, T1-T12, S1-S6
Yates and others (2000)	Effects of herbivory and non-native vegetation on woody plant recruitment in Salmon Gum woodlands in WA	B2, T9, T11

[a] WA, Western Australia

on badly degraded sites [S6] results in erosion and possibly salinization, shifting the system across another threshold creating a completely unproductive, dysfunctional landscape (not represented in Figure 1). At Burrendong Dam, erosion control efforts in the 1960s returned most of the badly degraded areas to mixed pasture (Colclough 1960). There was also some dense regeneration of tree seedlings, primarily *Callitris glaucophylla* with some *E. albens*. This is possibly a transitional state [S7], which may head towards [S2], [S4], or a state that does not currently exist [S8], depending on future fire regimes and understorey composition.

Land Management and Research Applications

As described with our proposed White Box model, STMs provide an important tool to gain a better understanding of the impacts of land-use history on ecosystems (Bestelmeyer and others 2004). Importantly, STMs can enable land managers and researchers to focus on ecosystem resistance and resilience, and how they affect the processes of vegetation change in modified or degraded systems (Brown 1994; Stringham and others 2003; Bestelmeyer and others 2004). Resistance refers to the ability of an ecosystem to absorb disturbance(s) and retain its characteristics. Resilience refers to the ability of an ecosystem to regain its original state after a change has occurred (e.g., Holling 1973; Westman 1978; Gunderson 2000). In terms of a STM, resistance is the ability of a ''state'' to remain stable despite various ongoing disturbances, whereas resilience of a system refers to reversibility between states across possible thresholds (provided that suitable ''triggers'' occur) referred to by Westoby and others (1989a) as ''opportunities'' for management.

In this way, our proposed White Box STM could be used to clarify the level of ''intactness'' of degraded White Box woodland sites and potential for restoration, and prevent land managers from making inappropriate comparisons to more ''intact'' sites, an exercise that only devalues any restoration efforts being made (Bestelmeyer and others 2003). The more successful restoration projects in fact are those that study the inherent resilience of the remnant patches, and apply interventions to exploit it, e.g., change grazing regimes to facilitate natural regeneration (McDonald 2001). By cataloguing the range of White Box woodland states, transitions, and thresholds that can occur in any given situation, a suitable framework is provided to identify the management actions and quantify restoration inputs to achieve a desired woodland ''state'' (Yates and Hobbs 1997b; Bestelmeyer and others 2003, 2004, Freudenberger and Harvey 2003).

Identification of Potential Barriers to Recovery

Identification of these thresholds or boundaries to recovery is critical to restoration of degraded White Box woodlands (Hobbs and Norton 2004; Suding and others 2004). For example, if a remnant ecosystem has passed a biotic threshold, efforts to force a transition back to an improved ''state'' may be easily affected by changes in disturbance regimes or species re-introductions. However, if a remnant ecosystem has passed an abiotic threshold such as compacted soils due to grazing, efforts to force a transition back to an improved state through species re-introductions may at best be problematic if soil conditions are not first repaired (Wright and Chambers 2002; Bestelmeyer and others 2003; Hobbs and Norton 2004). Positive feedbacks from species that characterize the system can also increase resistance of the system. Therefore, with greater attention in identifying thresholds, appropriate restoration goals can then be determined and subsequent prioritization of management actions can be undertaken (McIntyre and others 2000; Scheffer and Carpenter 2003; Suding and others 2004).

As illustrated in our proposed White Box woodland model, a remnant ecosystem may collapse under sustained grazing and not recover even when grazing pressure is reduced. In degraded White Box woodlands (Figures 1 and 2), thresholds appear to exist due to (1) constraints caused by biotic interactions and alterations, e.g., loss of propagules, changes in plant composition due to grazing and weed invasions, and (2) constraints caused by abiotic alterations, e.g., changes in soil compaction and nutrient levels. Such thresholds are prevalent in other grazed ecosystems (Whisenant 1999; McIntyre and others 2000; Wright and Chambers 2002; Schefer and Carpenter 2003; Hobbs and Norton 2004).

Recent studies have investigated whether soil phosphorus enrichment has facilitated the invasion of exotic species in White Box woodlands, creating a threshold that prevents recovery of native understorey species (Figures 1 and 2, B2). Allcock (2002a) found that increased nutrient levels create conditions that provide a competitive advantage to exotic species (e.g., *Echium plantagineum*) over native perennial grasses, because exotic seedlings grow faster and take over any gaps created by disturbance. Allcock (2002a) concluded that once exotic species established in high nutrient patches, they would persist despite the removal of grazing. These studies suggest that recovery after a long history of grazing is not assured (e.g., fencing to remove stock), and further intervention is required for native species to re-establish into degraded areas.

In similar studies, Prober and others (2002a, 2002b) carried out investigations of soil conditions in degraded White Box and *Eucalyptus melliodora* (Yellow Box) woodlands, to examine barriers to restoration, as described in Figures 1 and 2 (B2). By comparing soils of degraded sites to those in reference sites (see below), Prober and others (2002a, 2002b) found that soil nitrate was extremely low in reference sites, and there was a high correlation between annual exotic abundance to higher levels of soil nitrate in degraded sites. In contrast to findings by Allcock (2002a), available phosphorus did not differ between study sites, a finding that was partly attributed to differences in the presence of trees and sampling scales.

Prober and others (2002b) developed an amended STM for the understorey component of grassy White Box/Yellow Box woodlands, where ''states'' were defined along a generalized soil fertility gradient, based on the presence of ''keystone'' native perennial grasses and exotic annual species. The results of recent research by Prober and Thiele (2005) suggest that positive feedbacks between soil nutrients and understorey composition (e.g., in areas dominated by weeds, particularly former stock camps) can create barriers to restoration; therefore, further intervention is needed to improve soil and understorey conditions in degraded White Box woodland remnants (Prober and Thiele 2005). Already this work is gaining much interest among land managers in understanding changes in woodland ecosystems due to grazing, resilience, and barriers to successful restoration and management.

Use of STM to Set Management Goals

Management and restoration efforts (e.g., replanting of native species) are often plagued by ambiguities in both their goals and criteria for success (Aronson and others 1993; Hobbs 2003). To set appropriate goals requires sound knowledge of the ecosystem, particularly the desired ''state'' of the ecosystem, and an understanding of limiting and driving processes (both social and ecological). In most cases such knowledge is not available, so a value judgment must be made based on the level of degradation to take ''control'' of a site and attempt to improve it using various restoration techniques (Gunderson 2000). Hobbs and Norton (1996, p. 98) state that ''restoration can be viewed as an attempt to force transitions towards a desired *state*, and as requiring knowledge of the variables that need to be manipulated to achieve these transitions.'' As described earlier, a clear understanding of the ecosystem using a STM approach provides greater understanding into such ''transitions'' and ''states,'' provides a summary of the social and ecological processes driving the system, and can facilitate the setting of specific and measurable restoration goals to redirect the system development along a desired trajectory (Aronson and others 1993; Hobbs and Norton 1996).

As described in our STM for White Box woodlands (Figures 1 and 2), there is limited benefit in setting goals based on a concept of what the ecosystem was like before the introduction of stock by European settlers (< 1840s – S1), because many species are now extinct, soil conditions are vastly different, and natural disturbance regimes are difficult to re-implement (Smith and others 2000; Oliver and others 2002). Instead, the goal should be to establish self-sustaining vegetation that provides defined conservation and production benefits according to its existing ''state'' (Clewell and others 2000; McIntyre and others 2000). Managers need to accept that significant changes have occurred within local ecosystems, plan to retain what remains, and restore the processes that are critical (Smith and others 2000).

Determination of Reference Conditions

Complete restoration of degraded White Box woodlands is mostly unachievable, but we must decide how close we can get (Hobbs and Norton 1996). To achieve this, clear objectives are required regarding predetermined ecosystem parameters (e.g., native plant richness) to provide measurable management or restoration criteria (Prober and Thiele 2005). Within our STM framework, a useful approach could be to return target parameters to a predetermined range for each state, based on reference ecosystems for comparison and evaluation (Aronson and others 1993). In this way, each ''state'' or condition of a woodland remnant could be expressed with the use of similarity indexes between reference and degraded sites, as conceptualized in our STM (Wilson and Tupper 1982). Indices of vegetation change can be determined based on measurements of departure from a standard or reference site that represents the ''original,'' ''ideal,'' or ''best'' state for the ecosystem type (Wilson 1984; Aronson and others 1993). Patch or landscape scale parameters could be incorporated, in terms of composition, structure, or function (Freudenberger and Harvey 2003; Prober and Thiele 2005). The implication, with regard to our White Box STM, is that multiple states of an ecosystem can be classified objectively as variations to a reference state (as demonstrated by Prober and others 2002a, 2002b).

However, there are inherent problems in choosing reference sites, because one particular site deemed suitable as a reference site may be the product of a unique set of local environmental conditions (Turner 1989). Remnant vegetation communities are dynamic entities in which both the quality and composition fluctuate in response to continuous and recurrent natural and human disturbances (e.g., Wilson 1986; Hobbs 1987; Spooner and others 2004). Therefore, a reference *system* should be conceptualized from the collective attributes of multiple sites, to recognize the range of potential conditions that can exist (Clewell and others 2000). Multiple reference areas reduce the temptation to choose a rare, artificial, unique, or favored location as a standard (Wilson 1986). This would then incorporate real world dynamics, against which practical and attainable goals can be set (Oliver and others 2002). Otherwise, Hobbs and Norton (1996) argue that restoration projects focused on unattainable goals of achieving some ''historic condition'' are doomed to failure, being unrealistic, unachievable, and static. The development of STMs could therefore aid researchers to identify and gather information on reference system conditions (e.g., Prober and others 2002a), to then provide valuable information to land managers in setting appropriate and achievable goals.

Conclusions

In many agricultural areas of Australia, present-day woodland vegetation is often vastly different from that which existed prior to European settlement, even patches of high conservation value (Oliver and others

2002). State and transition models provide a useful framework to bridge the information gap between researchers and land managers, by revealing the range of states, transitions, and thresholds possible in any given locality. For this purpose, we have presented a STM for White Box woodlands, to stimulate new and innovative research activity of degraded woodland ecosystems. Ultimately the main purpose of any STM is to generate testable hypotheses about ecosystem functioning, and as a decision-support tool to aid land managers in forming restoration strategies (Yates and Hobbs 1997b). As demonstrated by Prober and others (2002b), with quantifiable data a STM provides a powerful tool to integrate theoretical knowledge and formulate management strategies.

An STM approach provides a useful framework to describe the vegetation dynamics of remnant White Box woodlands. Importantly, this STM highlights the role of exotic species and changes soil conditions in creating and maintaining barriers to any subsequent restoration activities. Observations at Burrendong Dam and the surrounding landscape support both the existence of and the proposed mechanisms behind the two ecosystem thresholds identified (Allcock 2002b). Empirical data (Allcock 2002a, 2002b; Prober and others 2002a, 2002b; Allcock and Hik 2004) generally support the mechanisms we have proposed for states, transitions, and thresholds.

Recent studies have demonstrated the potential of STMs using GIS and computer modeling techniques (e.g., Jeltsch and others 1997; Hemstrom and others 2002; Perry and Enright 2002; Hill and others 2003). For example, McIntosh and others (2003) used local expert knowledge to develop a simple STM of Mediterranean vegetation dynamics, which was then mathematically modeled using a combined predictive calculus and reasoning system. Such models use a series of ''what-if'' statements (e.g., what if disturbance frequency from grazing is increased, or excluded) to simulate vegetation dynamics (McIntosh and others 2003). Such techniques could be used to further develop our proposed White Box STM by testing hypotheses (e.g., whether soil phosphorus or soil nitrogen enrichment has facilitated the invasion of exotic species, creating a threshold that prevents recovery of native understorey species), and provide a methodology that strikes an appropriate balance between simplicity and realism (Plant and Vayssieres 2000).

There is an urgent need to develop practical techniques to restore functional woodland ecosystems in agricultural landscapes in Australia (e.g., Fry and Main 1993). STMs can provide the impetus for experimentation to develop better management and restoration techniques, and promote more proactive land management activities (Whalley 1994; Yates and Hobbs 1997b). Many studies have contributed to a greater understanding of the complexities and conservation importance of woodland ecosystems in Australia, but others have offered little due to the conceptual approach used, or ineffective communication of results. Given the growing awareness by land managers and researchers alike of the need to restore degraded White Box woodlands, the use of STMs may provide a useful framework for future research and management based on sound ecological criteria.

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References

Adamson D. A., M. D. Fox. 1982. Change in Australasian vegetation since European settlement. Pages 109–146 *in* J. M. B. Smith. (ed.), A history of Australasian vegetation. McGraw Hill, Sydney

Allcock, K. G., D. Board, D. Hik, A. Newsome, and R. Pech. 1999. Restoration based on ecological function: grazing management in an endangered Australian ecosystem. In Proceedings of the Annual Meeting of the Canadian Land Reclamation Association, 28–30 September 1999. Saskatoon, Saskatchewan

Allcock K. G. 2002a. Effects of phosphorus on growth and competitive interactions of native and introduced species found in White Box woodlands. Australian Ecology 27:638–646

Allcock, K. G. 2002b. Effects of grazing on vegetation dynamics in Australian White Box woodland. PhD Dissertation, Faculty of Graduate Studies and Research, University of Alberta, Edmonton, Canada

Allcock K. G., D. S. Hik. 2004. Survival, growth, and escape from herbivory are determined by habitat and herbivore species for three Australian woodland plants. Oecologia 138:231–241

Allen-Diaz B., J. W. Bartolome. 1998. Sagebrush-grass vegetation dynamics: comparing classical and state-transition models. Ecological Applications 8:795–804

Aronson J., C. Floret, E. Le Floc'h, C. Ovalle, R. Pontanier. 1993. Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands. I. A view from the south. Restoration Ecology 1:8–17

Beadle N. C. W. 1948. The vegetation and pastures of western New South Wales with special reference to soil erosion. Department of Conservation of New South Wales, Sydney
Bellamy J. A., J. R. Brown. 1994. State and transition models for rangelands. 7. Building a state and transition model for management and research on rangelands. Tropical Grasslands 28:247–255
Benson J. 1991. The effect of 200 years of European settlement on the vegetation and flora of New South Wales. Cunninghamia 2:343–370
Benson J. 1999. Setting the scene: the native vegetation of New South Wales. Native Vegetation Advisory Council of NSW, Sydney
Bestelmeyer B. T., J. R. Brown, K. M. Havstad, R. Alexander, G. Chavez, J. Herrick. 2003. Development and use of state-and-transition models for rangelands. Journal of Range Management 56:114–126
Bestelmeyer B. T., J. E. Herrick, J. R. Brown, D. A. Trujillo, K. M. Havstad. 2004. Land management in the American southwest: A state-and-transition approach to ecosystem complexity. Environmental Management 34: 38–51
Board, D. I. 2002. Seed dynamics and the restoration of White Box *Eucalyptus albens* woodland. MSc. Thesis, University of Alberta, Edmonton
Bork E. W., R. J. Hudson, A. W. Bailey. 1997. Upland plant community classification at Elk Island National Park, Alberta, Canada, using disturbance history and physical site factors. Plant Ecology 130:171–190
Briske D. D., S. D. Fuhlendorf, F. E. Smeins. 2003. Vegetation dynamics on rangelands: a critique of the current paradigms. Journal of Applied Ecology 40:601–614
Brown J. R. 1994. State and transition models for rangelands. 2. Ecology as a basis for rangeland management: performance criteria for testing models. Tropical Grasslands 28:206–213
Clayton-Greene K. A., D. H. Ashton. 1990. The dynamics of *Callitris columellaris/Eucalyptus albens* communities along the Snowy River and its tributaries in south-eastern Australia. Australian Journal of Botany 38:403–432
Clements F. E. 1928. Plant succession and indicators: a definitive edition of plant succession and plant indicators. Hafner Press, New York
Clewell, A., J. Rieger, J. Munro. 2000. Guidelines for developing and managing ecological restoration projects. Accessed 06 October 2004. http://www.ser.org/content/guidelines_ecological_restoration.asp
Cluff D., W. S. Semple. 1994. Natural regeneration: in 'mother natures' own time. Australian Journal of Soil and Water Conservation 7:28–33
Colclough J. D. 1960. Protection of foreshore lands of Burrendong Dam. Journal of the Soil Conservation Service of New South Wales 16:127–141
Curtis, D. J. 1990. Natural regeneration of eucalypts in the New England region. Pages 7–16 *in* Greening Australia (ed.), Sowing the Seeds, Proceedings of the Direct Seeding and Natural Regeneration Conference, Adelaide Convention Centre, 22–25 May 1990. Greening Australia, Deakin, Australia
Dublin H. T., A. R. E. Sinclair, J. McGlade. 1990. Elephants and fire as causes of multiple stable states in the Serengeti-Mara woodlands. Journal of Animal Ecology 59:1147–1164
Filet P. G. 1994. State and transition models for rangelands. 3. The impact of the state and transition model on grazing lands research, management and extension: a review. Tropical Grasslands 28: 214–222
Freudenberger D., J. Harvey. 2003. Assessing the benefits of vegetation enhancement for biodiversity: A draft framework. CSIRO Sustainable Ecosystems, Canberra
Friedel M. H. 1991. Range condition assessment and the concept of thresholds: a viewpoint. Journal of Range Management 44:422–426
Fry G., A. R. Main. 1993. Restoring seemingly natural communities on agricultural land. Pages 225–241 *in* D. A. Saunders, R. J. Hobbs, P. R. Ehrlich (eds.), Nature conservation 3: Reconstruction of fragmented ecosystems, global and regional perspectives. Surrey Beatty & Sons, Chipping Norton, Australia.
Gabriel O., A. Cibils, P. Borrelli, G. Humano. 1998. Stable states in relation to grazing in Patagonia: A 10-year experimental trial. Journal of Arid Environments 40:113–131
George M. R., J. R. Brown, W. J. Clawson. 1992. Application of non-equilibrium ecology to management of Mediterranean grasslands. Journal of Range Management 45:436–440
Grice A. C., N. D. MacLeod. 1994. State and transition models for rangelands. 6. State and transition models as aids to communication between scientists and land managers. Tropical Grasslands 28:241–246
Gunderson L. H. 2000. Ecological resilience in theory and application. Annual Review of Ecology and Systematics 31:425
Hemstrom M. A., M. J. Wisdom, W. J. Hann, M. M. Rowland, B. C. Wales, R. A. Gravenmier. 2002. Sagebrush-Steppe vegetation dynamics and restoration potential in the interior Columbia basin, USA. Conservation Biology 16:1243–1255
Hill M. J., R. Braaten, G. M. McKeon. 2003. A scenario calculator for effects of grazing land management on carbon stocks in Australian rangelands. Environmental Modelling and Software 18:627–644
Hobbs R. J. 1987. Disturbance regimes in remnants of natural vegetation. Pages 233–240 *in* D. A. Saunders, G. W. Arnold, A. A. Burbridge, A. J. M. Hopkins (eds.), Nature conservation: the role of remnants of native vegetation. Surrey Beatty & Sons, Chipping Norton, Australia
Hobbs R.J. 2003. Ecological management and restoration: assessment, setting goals and measuring success. Ecological Management and Restoration 4:S2–S3
Hobbs R.J., A.J.M. Hopkins. 1990. From frontier to fragments: European impact on Australia's vegetation. Proceedings of the Ecological Society of Australia 16:93–114
Hobbs R. J., D. A. Norton. 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology 4:93–110
Hobbs R. J., D. A. Norton. 2004. Ecological filters, thresholds and gradients in resistance to ecosystem reassembly. Pages 72–95 *in* V. Temperton, R. J. Hobbs, T. Nuttle, S. Halle (eds.), Assembly rules and restoration ecology: Bridging the gap between theory and practice. Island Press, Washington, DC.
Hodgekinson K.C., J.D. Cooke. 1995. The ecology of perennial grass collapse under grazing. Pages 203–277 *in* M.J. Page and T.S. Beatel (eds.), Ecological Research and Management in the Mulgalands: Conference Proceedings, University of Queensland, Gratton Collage
Holling C. S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:2–23
Huntsinger L., J. W. Bartolome. 1992. Ecological dynamics of Quercus dominated woodlands in California and southern Spain: a state-transition model. Vegetatio 99–100:299–305
Jeltsch F., S. J. Milton, W. R. J. Dean, N. Vanrooyen. 1997. Analysing shrub encroachment in the southern Kalahari: a grid-based modelling approach. Journal of Applied Ecology 34:1497–1508

Kepe T., I. Scoones. 1999. Creating grasslands: social institutions and environmental change in Mkambati area, South Africa. Human Ecology 27:29–54

Krebs C. J. (ed.). 1999. Ecology: The experimental analysis of distribution and abundance (4th ed.). Harper Collins College Publishers, New York

Landsberg J., F. R. Wylie. 1991. A review of rural dieback in Australia. Growback 91:3–11

Laycock W. A. 1991. Stable states and thresholds of range condition on North American rangelands: a viewpoint. Journal of Range Management 44:427–433

Lodge, G. M., R. D. B. Whalley. 1989. Native and natural pastures on the northern slopes and tablelands of New South Wales. Technical bulletin no. 35, NSW Department of Agriculture and Fisheries, Sydney

Logan J. M. 1957a. Grassland research for soil conservation on Burrendong foreshores I. Journal of the Soil Conservation Service of New South Wales 13:50–69

Logan J. M. 1957b. Grassland research for soil conservation on Burrendong foreshores II. Journal of the Soil Conservation Service of New South Wales 13:198–209

Lunt I. D. 1991. Management of remnant, lowland grasslands and grassy woodlands for nature conservation: a review. Victorian Naturalist 108:56–66

Lunt I. D. 1995. European management of remnant grassy forests and woodlands in south-eastern Australia: past, present and future? Victorian Naturalist 112:239–249

Lunt I. D. 1997. Germinable soil seed banks of anthropogenic native grasslands and grassy forest remnants in temperate south-eastern Australia. Plant Ecology 131:21–34

Lunt I. D., J. W. Morgan. 1999. Vegetation changes after 10 years of grazing exclusion and intermittent burning in a *Themeda triandra* (Poaceae) grassland reserve in south-eastern Australia. Australian Journal of Botany 47:537–552

Lunt I. D., P. G. Spooner. 2005. Using an historical ecology to understand patterns of biodiversity in fragmented agricultural landscapes. Journal of Biogeography 32:1859–1873

May R. 1977. Thresholds and breakpoints in ecosystems with a multiplicity of stable states. Nature 269:471–477

McDonald T. 2001. Making bush regeneration work: what are we working with? Ecosystem resilience and the restoration of damaged plant communities. Nature Conservation Council of NSW, Sydney

McIntosh B. S., R. I. Muetzelfeldt, C. J. Legg, S. Mazzoleni, P. Csontos. 2003. Reasoning with direction and rate of change in vegetation state transition modelling. Environmental Modelling and Software 18:915–927

McIntyre S., S. Lavorel. 1994. How environmental and disturbance factors influence species composition in temperate Australian grasslands. Journal of Vegetation Science 5:373–384

McIntyre S., J. G. McIvor, N. D. MacLeod. 2000. Principles for sustainable grazing in eucalypt woodlands: landscape-scale indicators and the search for thresholds. Pages 92–100 *in* P. Hale, A. Petrie, D. Moloney, P. Sattler (eds.), Management for sustainable ecosystems. Centre for Conservation Biology, University of Queensland, Brisbane.

Moore C. W. E. 1953. The vegetation of the south-eastern Riverina, New South Wales. II. The disclimax communities. Australian Journal of Botany 1:548–567

Moore R. M. 1973. South-eastern temperate woodlands and grasslands. Pages 169–190 *in* R. M. Moore. (ed.), Australian grasslands. Australian National University Press, Canberra

Noble I. R., R. O. Slatyer. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43:5–21

O'Connor T. G. 1991. Local extinction in perennial grasslands: a life-history approach. The American Naturalist 137:753–773

Oliver I., P. L. Smith, I. Lunt, D. Parkes. 2002. Pre-European vegetation, naturalness and vegetation condition: what are the implications for biodiversity conservation? Ecological Management and Restoration 3:176–178

Packard S. 2000. Restoring oak woodlands. Pages 145–167 *in* W. Throop. (ed.), Environmental restoration: ethics, theory and practice. Humanity Books, New York

Perry G. L. W., N. J. Enright. 2002. Humans, fire and landscape pattern: understanding a maquis-forest complex, Mont do, New Caledonia, using a spatial 'state-and-transition' model. Journal of Biogeography 29:1143–1158

Petraitis P. S., R. E. Latham. 1999. The importance of scale in testing the origins of alternative community states. Ecology 80:429–448

Pettit N. E., R. H. Froend, P. G. Ladd. 1995. Grazing in remnant woodland vegetation: changes in species composition and life form groups. Journal of Vegetation Science 6:121–130

Pickett S. T. A., S. L. Collins, J. J. Armesto. 1987. Models, mechanisms and pathways to succession. The Botanical Review 53:335–371

Plant R. E., M. P. Vayssieres. 2000. Combining expert system and GIS technology to implement a state-transition model of oak woodlands. Computers and Electronics in Agriculture 27:71–93

Plant R. E., M. P. Vayssieres, S. E. Greco, M. R. George, T. E. Adams. 1999. A qualitative spatial model of hardwood rangeland state-and-transition dynamics. Journal of Range Management 52:51–59

Prober S. M. 1996. Conservation of the grassy White Box woodlands: Rangewide floristic variation and implications for reserve design. Australian Journal of Botany 44:57–77

Prober S. M., K. R. Thiele. 1993. The ecology and genetics of remnant grassy White Box woodlands in relation to their conservation. Victorian Naturalist 110:30–36

Prober S. M., K. R. Thiele. 1995. Conservation of the grassy White Box woodlands: relative contributions of size and disturbance to floristic composition and diversity of remnants. Australian Journal of Botany 43:349–366

Prober S. M., K. R. Thiele. 2005. Restoring Australia's temperate grasslands and grassy woodlands: integrating function and diversity. Ecological Management and Restoration 6:16–27

Prober S. M., I. D. Lunt, K. R. Thiele. 2002b. Determining reference conditions for management and restoration of temperate grassy woodlands: relationships among trees, topsoils and understorey flora in little-grazed remnants. Australian Journal of Botany 50:687–697

Prober S. M., K. R. Thiele, I. D. Lunt. 2002a. Identifying ecological barriers to restoration in temperate grassy woodlands: soil changes associated with different degradation states. Australian Journal of Botany 50:699–712

Prober S. M., K. R. Thiele, E. Higginson. 2001. The Grassy Box woodlands conservation management network: picking up the pieces in fragmented woodlands. Ecological Management and Restoration 2:179–188

Reed P. 1991. An historical analysis of the changes to the forests and woodlands of New South Wales. Pages 393–406 *in* D. Lunney (ed.), Conservation of Australia's forest fauna. Royal Zoological Society of NSW, Mossman, Australia.

Scheffer M., S. R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology and Evolution 18:648–656

Sivertsen D. 1993. Conservation of remnant vegetation in the Box and Ironbark lands of New South Wales. Victorian Naturalist 110:24–29

Smith P. L., B. Wilson, C. Nadolny, D. Lang. 2000. The ecological role of the native vegetation of New South Wales. Native Vegetation Advisory Council of NSW, Sydney

Spooner P. G., I. D. Lunt, W. Robinson. 2002. Is fencing enough? The short-term effects of stock exclusion in remnant grassy woodlands in southern NSW. Ecological Management and Restoration 3:117–126

Spooner P. G., I. D. Lunt, S. V. Briggs, D. Freudenberger. 2004. Effects of soil disturbance from roadworks on roadside shrubs in a fragmented agricultural landscape. Biological Conservation 117:393–406

Stockwell T. G. H., R. T. Andison, A. J. Ash, J. A. Bellamy, R. M. Dyer. 1994. State and transition models for rangelands. 9. Development of state and transition models for pastoral management of the Golden Beard grass and limestone grass pasture lands of NW Australia. Tropical Grasslands 28:260–265

Stringham T. K., W. C. Krueger, P. L. Shaver. 2003. State and transition modelling: an ecological process approach. Journal of Range Management 56:106–113

Suding K. N., K. L. Gross, G. R. Houseman. 2004. Alternative states and positive feedbacks in restoration ecology. Trends in Ecology & Evolution 19:46–53

Taylor J., N. MacLeod, A. Ash. 1994. State and transition models: bringing research, extension and management together. Tropical Grasslands 28:193–194

Thiele K. R., S. M. Prober. 2000. Reserve concepts and conceptual reserves: options for the protection of fragmented ecosystems. Pages 351–358 *in* R. J. Hobbs, C. J. Yates (eds.), Temperate eucalypt woodlands in Australia. Surrey Beatty & Sons, Chipping Norton, Australia

Turner M. G. 1989. Landscape ecology: the effect of pattern on process. Annual Review of Ecology and Systematics 20:171–197

Wedin D. A. 1999. Nitrogen availability, plant-soil feedbacks, and grassland stability. Pages 193–197 *in* D. Eldridge, D. Freudenberger (eds.), Proceedings of the 6th International Rangeland Congress. CSIRO, Aitkenvale, Australia.

Westman W. E. 1978. Measuring the inertia and resilience of ecosystems. Bioscience 28:705–710

Westoby M., B. H. Walker, I. Noy-Meir. 1989a. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42:266–274

Westoby M., B. H. Walker, I. Noy-Meir. 1989b. Range management on the basis of a model which does not seek to establish equilibrium. Journal of Arid Environments 17:235–239

Whalley R. D. B. 1994. State and transition models for rangelands. 1. Successional theory and vegetation change. Tropical Grasslands 28:195–205

Whisenant S.G. 1999. Repairing damaged wildlands: A process-orientated, landscape-scale approach. Cambridge University Press, Cambridge

Wilson A. D. 1984. Points of reference in the assessment of change in vegetation and land condition. Australian Rangeland Journal 6:69–74

Wilson A. D. 1986. The monitoring of changes in range condition: a multivariate site potential approach. Pages 517–521 *in* P. J. Joss, P. W. Lynch, O. B. Williams (eds.), Proceedings of the 2nd International Rangeland Congress. Australian Academy of Science, Canberra.

Wilson A. D. 1990. The effect of grazing on Australian ecosystems. Proceedings of the Ecological Society of Australia 16:235–244

Wilson A. D., G. J. Tupper. 1982. Concepts and factors applicable to the measurement of range condition. Journal of Range Management 35:684–689

Windsor D. M. 1999. A review of factors affecting regeneration of Box woodlands in the Central Tablelands of New South Wales. Pages 271–285 *in* R. J. Hobbs, C. J. Yates. (eds.), Temperate eucalypt woodlands in Australia: Biology, conservation, management and restoration. Surrey Beatty & Sons, Chipping Norton, Australia.

Wright J. M., J. C. Chambers. 2002. Restoring riparian meadows currently dominated by Artemisia using alternative state concepts—above-ground vegetation response. Applied Vegetation Science 5:237–246

Yates C. J., R. J. Hobbs. 1997a. Temperate eucalypt woodlands: a review of their status, processes threatening their persistence and techniques for restoration. Australian Journal of Botany 45:949–973

Yates C. J., R. J. Hobbs. 1997b. Woodland restoration in the western Australian wheatbelt: a conceptual framework using a state and transition model. Restoration Ecology 5:28–35

Yates C. J., D. A. Norton, R. J. Hobbs. 2000. Grazing effects on plant cover, soil and microclimate in fragmented woodlands in south-western Australia: implications for restoration. Austral Ecology 25:36–47