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Insight, part of a Special Feature on Exploring Resilience in Social-Ecological Systems

Resilience and Regime Shifts: Assessing Cascading Effects

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ABSTRACT. Most accounts of thresholds between alternate regimes involve a single, dominant shift defined by one, often slowly changing variable in an ecosystem. This paper expands the focus to include similar dynamics in social and economic systems, in which multiple variables may act together in ways that produce interacting regime shifts in social-ecological systems. We use four different regions in the world, each of which contains multiple thresholds, to develop a proposed "general model" of threshold interactions in social-ecological systems. The model identifies patch-scale ecological thresholds, farm- or landscape-scale economic thresholds, and regional-scale sociocultural thresholds. "Cascading thresholds," i.e., the tendency of the crossing of one threshold to induce the crossing of other thresholds, often lead to very resilient, although often less desirable, alternative states.

Key Words: *thresholds;regime shifts;social-ecological systems;system interactions; cascading effects*

INTRODUCTION

The last three or four decades have fostered a revolution in the way scientists think about the world: instead of orderly and well behaved, they now view it as complex and uncertain. Many of the authors of this special issue, particularly those who are ecologists, trace the genesis of their thinking on these topics to the seminal paper by Holling in 1973, but many others pioneered and contributed to this growing awareness. A very incomplete list would include Adams (1978) in archeology, Schumpeter (1950) in economics, and Goldstone (1991) in history.

All of these thinkers, both named and unnamed, have suggested that the seemingly stable states we see around us in nature and in society, such as woody savannas, democracies, agro-pastoral systems, and nuclear families, can suddenly shift out from underneath us and become something new, with internal controls and aggregate characteristics that are profoundly different from those of the original. The types of changes that involve alterations in internal controls and feedbacks are often called "regime shifts" (Scheffer and Carpenter 2003, Folke et al. 2004). Although it has always been recognized that these regime shifts can occur because of external perturbations, the advances promoted by these pioneer thinkers suggest that these shifts also occur because of complex interactions within the system that operate across scales, with myriad localized interactions among smaller entities serving as a source of adaptation and novelty, and larger-scale emergent constructs such as norms, institutions, or climatic regimes constraining the behavior and states at smaller scales. This possibility of sudden conversion has profound implications not only for our understanding of how the world is structured but also for how we manage the Earth's environmental systems, including their coupling with our own socioeconomic systems.

Resilience is defined as "the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" (Walker et al. 2004). A regime shift, then, initially represents a loss of resilience, in that former functions, structures, feedbacks, and therefore identities (Cumming and Collier 2005) give way to new versions. However, one of the central points of this paper is that crossing a single threshold between alternative regimes often leads to a "cascading effect" in which multiple thresholds across scales of space, time, and social organization and across ecological, social, and economic domains may be breached. The regime that this

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cascading effect ultimately produces has a tendency to be highly resilient and resistant, for instance, to management strategies that might seek to restore the earlier regime.

REGIME SHIFTS, BASINS OF ATTRACTION, AND HYSTERESIS

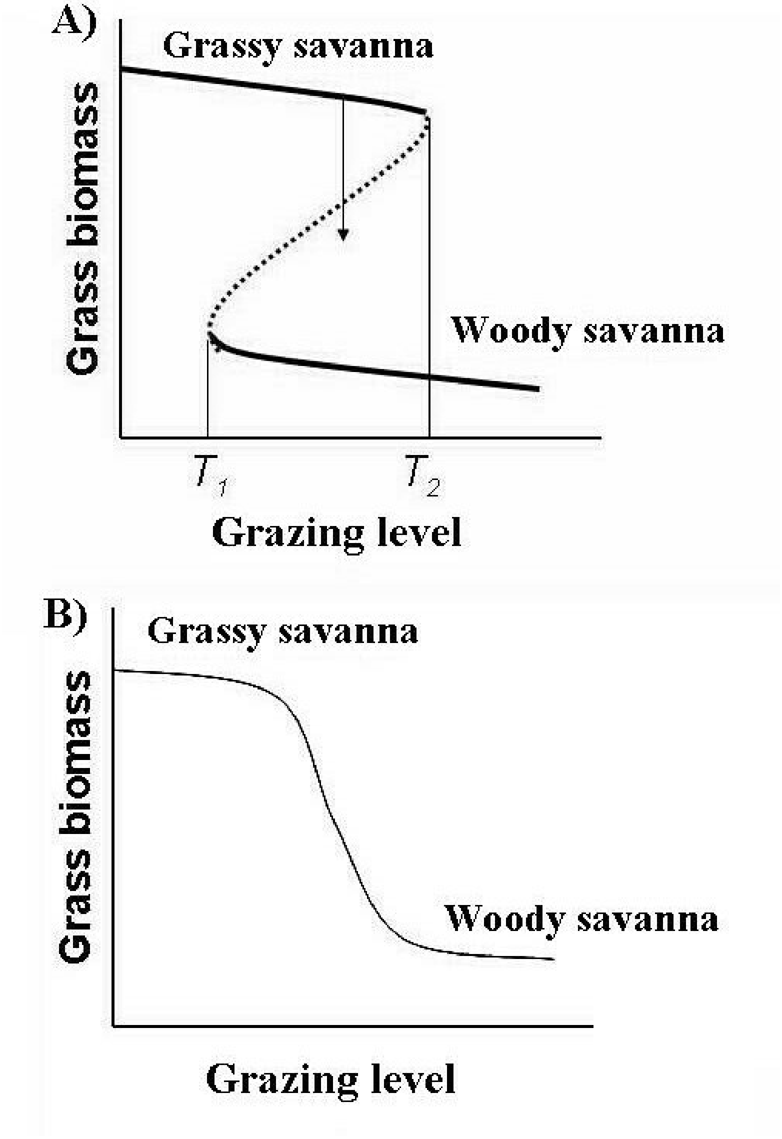
Before embarking on our analysis, it is worth offering brief definitions of various key concepts and the relationships among them. Consider, for instance, a savanna system that has been observed over very long time periods to occupy one of two dominant states: a grassy savanna with high grass biomass and low shrub biomass or a woody savanna with high shrub biomass and low grass biomass. A possible representation of the states of the system is shown in Fig. 1A, with the upper solid curve representing the state of a grassy savanna and the lower solid curve representing the woody savanna. If the system is initially in the high grass state and grazing pressure increases somewhat, i.e., moves to the right along the x-axis, grass levels will be only slightly depressed, and the system will still effectively be a grassy savanna. However, if grazing reaches a particular critical point (T_2 in Fig. 1A), this state is suddenly lost, and there is a shift to a woody state. Reducing grazing only slightly, to the level it had reached just before the regime shift, will not alter this conversion; grazing must be reduced drastically to level T_1 before the grass regime can be restored, which introduces some degree of irreversibility. This effect is known as hysteresis, from the Greek *husteros,* meaning “late.”

May (1977) refers to both T_1 and T_2 as a “threshold,” i.e., the point at which one relatively stable state or regime gives way to another. However, Scheffer et al. (2001) point out explicitly, and May implicitly, that there is another type of threshold operating in the system, notably the dotted line or unstable equilibrium separating the two regimes. All states above the dotted line and between T_1 and T_2 will tend toward the upper branch, and all below it toward the lower branch. Because resilience is defined as as “the capacity of a system to absorb disturbance ... [and] still retain essentially the same function, structure, identity and feedbacks” (Walker et al. 2004), the distance between each branch and the dotted line is a measure of resilience.

In this particular example, the upper and lower branches represent true alternative states. It should be noted, however, that if the “fold” in the hysteresis curve were to be relaxed (Fig. 1B), the system would respond more smoothly to changes in grazing. Shifts from grassy to woody savannas would still be possible, but only one possible state could exist for any level of grazing in the system, i.e., there could be no alternative states. The controlling variable, the x-axis, still exhibits something of a threshold in that, once it passes a critical point, the conversion from grassy to woody savanna or vice versa would occur, although that change would be much smoother than a conversion with a profound hysteretic effect. Also, although they are not true alternative stable states, the differences between a grassy and a woody savanna can be quite large. As such, we will call a regime shift any drastic change in the properties of a system resulting from smaller perturbations or smooth changes in independent controlling variables, similar to the definitions used by Muradian (2001) and Walker and Meyers (2004).

Muradian also notes that “ ... definitions of thresholds can be arbitrary in the sense that it depends on the temporal and spatial scales adopted. &#8221 Levin (1992) makes a similar observation for pattern generally in ecological systems. A further consideration of the thresholds depicted in Fig. 1A reinforces that point. Whether or not the system crosses thresholds T_1 and T_2, for instance, depends in part on ecological conditions or management decisions, e.g., the number of grazers in the system. However, Carpenter (2003) notes that the position of the thresholds themselves can change because of slowly changing variables in the system, such as nutrients in soil sediments. In the Hollingesque view of ecological systems (Gunderson and Holling 2002), large-scale components change slowly, whereas smaller-scale components change more rapidly. To the extent that this holds, thresholds might shift as the result of changes happening at higher levels of ecological organization. Redman and Kinzig (2003), however, speculate that the opposite may occur in social systems: larger levels of social organization may change rapidly, with lower levels demonstrating greater longevity; this leaves open the possibility that changes in the position of the thresholds are being introduced from lower organizational scales. Either way, the position of these thresholds, and the possibilities for crossing them, depend critically on what is happening at other spatial, temporal, and organizational scales of the system. However, few analyses of coupled social-ecological systems have been able to rigorously relate threshold dynamics at

Fig. 1. A) Illustration of a hysteresis effect for a shrub-grass savanna. Initially, grazing has little effect on grass biomass, but eventually a threshold is reached at which a slight increase in grazing (T_2) causes an ecological regime shift to a situation of low grass-high shrub biomass. Decreasing the grazing only slightly will not suffice to recover the high grass biomass state; it must be decreased to a value T_1 before the grassland savanna is restored. The dotted line between the upper and lower branches represents an unstable equilibrium. States of the system above this dotted line and between T_1 and T_2 will reach the grassy savanna or upper branch, whereas those below will result in the woody savanna or lower branch. The arrow represents a state excursion that crosses this second type of threshold (the dotted line), resulting in a switch from grassy to woody savanna. B) A transition from a grassy to woody savanna in the absence of a hysteretic effect. Changes in grazing pressure lead to a relatively smooth transition from grassy to woody savanna, with little apparent irreversibility (but see text).



particular analytical scales to threshold dynamics at other scales.

Scheffer et al. (2001) address excursions across the unstable equilibrium (the dotted line in Fig. 1A) and note that both external stochastic events and internal dynamics can drive the state of the system across this threshold. Scheffer et al. invoke limit cycles or strange attractors as one possible set of these internal dynamics. A reading of Gunderson and Holling (2002), among others, suggests another possibility, namely, that the dynamics of subcomponents of the system, i.e., lower levels of organization or smaller patches, including the possibility that these subcomponents themselves have crossed a critical threshold and undergone a state shift, may introduce perturbations that can cause changes in the state of the system at the focal scale and thus breaches of the thresholds that separate regimes.

Walker and Meyers (2004) and Carpenter and Brock (2004) also illustrate the possibility that regime shifts can occur because of interactions across social, ecological, and economic domains, and not just as the result of interactions across scales within a particular domain. Westley et al. (2002) and Kinzig (2001) further demonstrate the need to couple ecological and socioeconomic domains when examining the dynamics of systems of natural resource management, hereafter referred to as social-ecological systems. In particular, many of the ecological states represented along the x-axis of, e. g., Figs. 1A or 1B may be very difficult or impossible to achieve, given the social and cultural constraints or regime shifts operating in the system. If those constraints are not acknowledged, then it would appear to an analyst or manager that a “reversible” threshold, such as that in Fig. 1B, can be crossed in either direction, when in fact it cannot because certain portions of the x-axis are simply inaccessible. We return to this point later.

In spite of its importance for understanding system dynamics, we know of no analyses that have been able to present a general framework, either conceptually or mathematically, for analyzing the consequences of interactions of regime shifts across scales and domains. Such an undertaking is, indeed, quite difficult, and no single paper can give it a comprehensive treatment. In this paper, we embark on the early steps of such an endeavor by presenting a general conceptual framework for understanding interacting regime shifts and by analyzing this framework in four examples of natural resource management: the Causse Méjan region of France, the Goulburn-Broken Catchment of Australia, the western Australian wheatbelt, and the Madagascar dry forests. The scientists studying each of these regions joined together for a cross-system comparison at a workshop in May 2004 because they recognized that the current literature on thresholds, resilience, and regime shifts, limited as it was by particular focal scales and domains, was not allowing an adequate description of the dynamics they were observing in their systems. Instead, each of them had a number of different threshold effects that had resulted in regime shifts or were considered very likely to. However, there was no available integrating framework for examining these thresholds and how they might interact.

In establishing our conceptual framework and in discussing the examples, we are largely exploring these two propositions of Walker et al. (2006):

- Proposition 6: The ecological and social domains of social-ecological systems can be addressed in a common conceptual, theoretical, and modeling framework; and
- Proposition 12: Social-ecological systems have multiple interacting thresholds, giving rise to multiple pairs of alternate regimes, only a few of which are feasible.

However, our analysis touches on several other propositions as well, including the following:

Proposition 1: Multiple modes of reorganization are possible during phases of release and renewal in a social-ecological system. Because of this, managers need to consider multiple approaches during such periods;

Proposition 3: Cross-scale interactions critically determine the form of the subsequent adaptive cycle at any particular focal scale; and

Proposition 4: Critical changes in social-ecological systems are determined by a small set of three to five key variables, i.e., the “rule of hand.” To understand change in systems, it is important to identify this small set.

In the next section, we present our general conceptual framework, followed by an analysis of this framework in the four different examples. We finish with some concluding remarks about the consequences of managing complex natural-resource systems.

A GENERAL CONCEPTUAL FRAMEWORK

The initial discussion of the four regions revealed that each had thresholds or potential thresholds in three domains, i.e., the ecological, economic, and sociocultural, and at three scales, i.e., small = patch, medium = farm or individually owned or managed entity, and large = region. We wished to examine the regime shifts that can occur at each of these scales and in each of these domains as well as the possibility that a regime shift in one might trigger regime shifts at other scales or in other domains. Regime shifts of this type will be referred to as “interacting regime shifts” or “cascading regime shifts.” In theory, a multitude of interacting regime shifts is possible, ranging from a single regime shift confined to a particular domain and a single scale to regime shifts that trigger others in cascading fashion until regime shifts in all nine, i.e., three domains and three scales, occur (see Fig. 2A).

However, in analyzing the examples, we found that only a subset of possible regime-shift interactions or cascades actually occurred. In particular, only five of the domain-scale combinations featured in any of our four examples, and only four featured in all of them. This simplified subset of the possibilities is shown in Fig. 2B. More importantly, we found in analyzing the four cases that these cascading regime shifts across the four or five domain-scale combinations always led to highly resilient new regimes or effectively irreversible changes that were frequently less desirable than the original regime.

It should be noted that we do not, in our analysis, distinguish between regime shifts caused by breaching different types of thresholds, such as T_1 and T_2 in Fig. 1A, the unstable equilibrium in Fig. 1A, or the more gradual threshold in Fig. 1B. These thresholds may not be operating independently; for example, dynamics at smaller or larger scales could simultaneously both shift the position of T_1 and move the state of the system across an unstable equilibrium at a particular focal scale. We currently lack the general model that would be required to identify the different types of thresholds operating in different domains and at different scales; we thus use “thresholds” quite generally to encompass all of these possibilities and focus largely on the regime shifts that result.

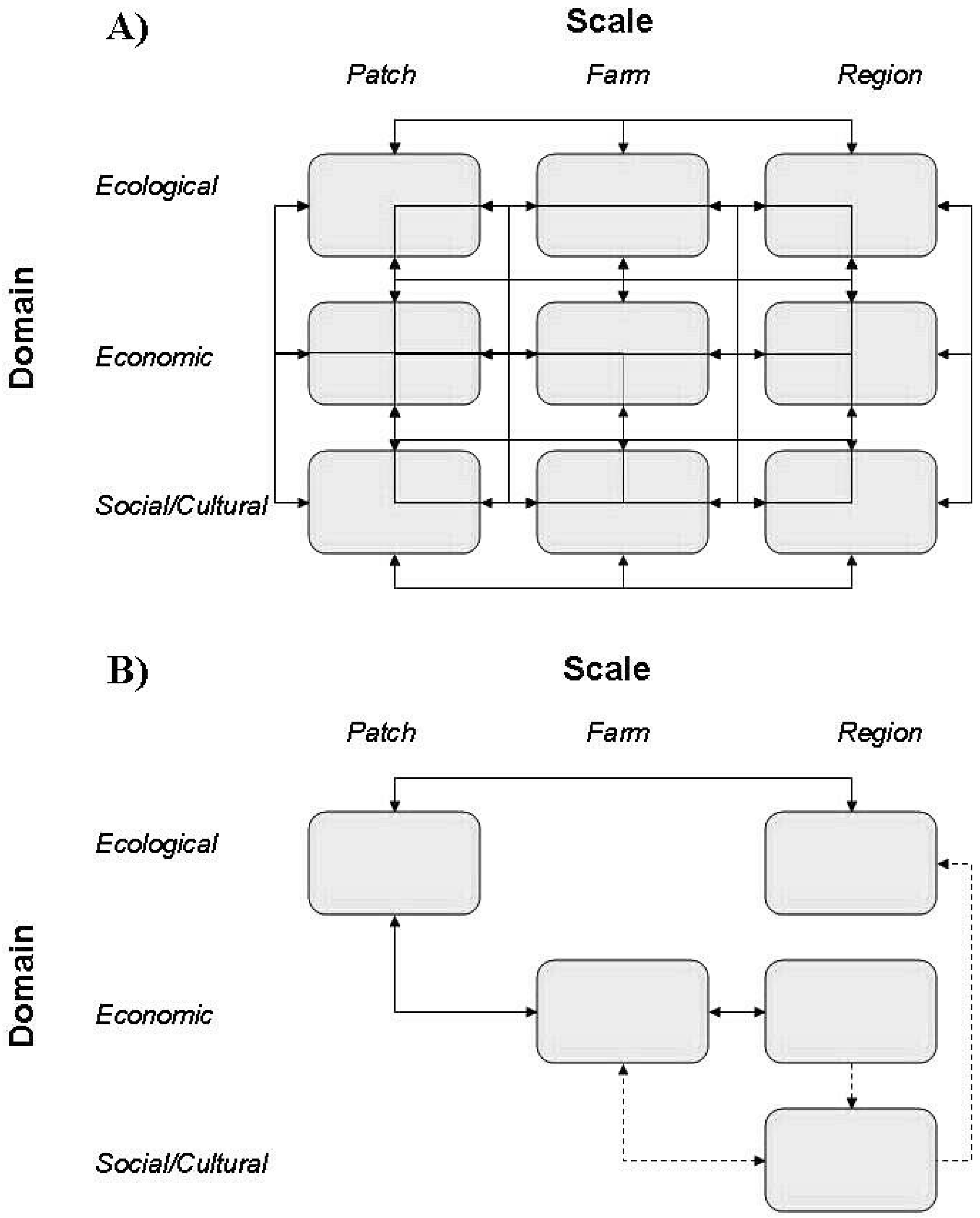
THE CAUSSE MÉJAN CASE STUDY: THE PARADOX OF FEDOU CHEESE

The Causse Méjan region of France is characterized culturally and gastronomically by its production of Roquefort and Fedou cheeses, which are made from sheeps’ milk, and ecologically by its unique native grassland habitat. In recent decades, this grassland habitat has been steadily declining because of pine encroachment. At some point, the proportion of pine could reach a critical threshold at which the remaining grassland patches would be isolated from each other, and species endemic to the grassland would decline precipitously because of low population sizes and lack of genetic exchange. Because the region is surrounded by steep cliffs and deep canyons, recovery of the grassland species through in-migration would be impossible. Retaining native grassland habitat therefore means controlling pine encroachment.

The regional pine coverage is, in part, a function of the production systems chosen by local farmers. These include the production of lamb for meat; Fedou cheese, which is specific to the Causse Méjan region; Roquefort cheese, which is specific to a larger *bassin d’approvisionnement* that includes Causse Méjan; and timber. Fedou cheese commands a higher price than Roquefort and, also for cultural and technical reasons, is preferred for cheese production in the region. Pine encroachment can be controlled with grazing or mechanical clearing of seedlings. Because of the different grazing and feed requirements of the different production systems, meat production requires the highest levels of farm-level grassland habitat, followed by Fedou cheese, Roquefort farms, and timber farms.

In theory, any proportion of regional tree cover, from very high, i.e., all timber farms, to low, i.e., all meat farms, is possible, depending on the regional frequency of the different production systems. Currently, regional pine coverage is about 30%, with some 80% of the farms devoted to cheese production and 20% to meat production. Given that the critical threshold that pine coverage would need to reach to significantly fragment native grassland is about 50%, it appears that this system has a significant buffer against a regional ecological regime shift and is thus relatively resilient.

Fig. 2. A) A generalized model of threshold interactions showing all possible combinations of domains and scales and the possible interactions between regime shifts at various domain-scale combinations. B) The critical combinations of domains, scales, and interactions across the four examples. Solid lines indicate interactions, e.g., regime shifts at one scale combination triggering regime shifts at another, that occured in all four case studies. Dotted lines indicate interactions that occur in only one or two of the case studies.



However, the central thesis of this paper is that regime shifts that occur at other scales, i.e., plot level or farm level, or in other domains, i.e., the cultural or economic in addition to the ecological, may make the crossing of this type of regional ecological threshold more or less likely. What are the other dominant regime shifts operating in this system, and how do they influence the likely future possibilities for regional tree coverage?

The production system in this region has survived because cereal cropping and meat, wool, and cheese production have created a relatively stable ecological system based on native steppe grasslands. Consideration of the cultural domain, in addition to the ecological domain, would initially reinforce the assessment of a reasonable level of resilience. There is a strong regional identity based on the production of Fedou cheese and strong cultural influences directing farmers toward its production. Therefore, it would appear that cultural pressure would reduce the likelihood that too many farmers would forego the production of Fedou cheese.

However, regime shifts in other domains and at other scales may alter this. One critical element concerns patch-level conversion from grassland to woodland; patches are smaller than farm systems. Given current levels of regional pine encroachment, there exists the possibility that spatially heterogeneous seed dispersal will result in a high seed rain on some patches, overwhelming attempts at control and resulting in a grassland to woodland shift at the patch level, i.e., an ecological regime shift at a small scale. This threat has been exacerbated by the National Forest Fund program, which in the 1970s planted many trees that are now coming into maturity and contributing to seed dispersal in this region.

If enough patches on a farm revert to woodland, then meat and Fedou production, which rely on sufficient grassland grazing sites, may become impossible. The small-scale ecological regime shift will cause a farm-scale economic regime shift as farmers are forced to adopt Roquefort or timber production systems. The regime shifts discussed to this point, and their interactions, are shown in Fig. 3A.

As farmers shift away from Fedou production, their identities at the household level cease to correspond to the larger cultural identity organized around the production of the local cheese. As more and more farmers fall into this category, the cultural identity that compels Fedou production begins to weaken. Moreover, the very existence of Fedou cheese depends on a critical mass of farmers in the Causse Méjan region participating in its production. If the numbers become too few, the Fedou label ceases to exist, because milk from outside the region cannot replace local milk in cheese production. Once this threshold is reached, all the remaining farmers engaged in Fedou production will be forced to engage in different production activities, probably Roquefort production or timber production, because woodland levels on the Fedou farms may make viable meat production impossible. The farm-level economic regime shift can create a regional cultural regime shift. The regime shifts in each of the various domains are shown in Table 1, and the interactions among them are shown in Fig. 3B.

If this regional cultural threshold is crossed, it collapses the possible futures to those in which there is no Fedou production. More importantly, this change is not experienced gradually, in that Fedou cheese farmers are not incrementally lost from the system; instead, they are lost abruptly as the ecological, economic, and cultural regime shifts interact to force out Fedou production. Thus, the range of possible futures that a naïve representation might create proves to be misleading. The full complement of interacting regime shifts (Fig. 3B) leads to a scenario in which two drastically different futures are possible: one based primarily on Fedou production, with careful control of regional pine coverage, and one based primarily on other production systems, with increasing pine encroachment. This latter regime, once reached through a series of cascading and interacting regime shifts across scales and domains, is highly resilient. In particular, the removal of woodland and the restoration of a lost cultural identity seem irreversible on time scales relevant to the managers and citizens of the region.

THE GOULBURN-BROKEN CATCHMENT

The irrigated region of the lower Goulburn-Broken Catchment (GBC) is one of the most important agricultural regions in Australia (see Lawson and Walker 2006). The clearing of native vegetation more than a century ago, however, set in train changes in the catchment's hydrological balance that are today taking their toll. Historically, deep-rooted native vegetation maintained groundwater

Fig. 3. Interactions among regime shifts in the Causse Méjan case study. A is a partial assessment, and B is the complete assessment (see text). The boxes represent potential thresholds in various domains, e.g., ecological vs. economic, at various scales. For instance, when grazing pressure is low, there is a threshold of pine seed rain that, once crossed, prevents mechanical clearing of seedlings and leads to a regime shift from grassland to woodland at the patch scale. The arrows between boxes show interactions among thresholds (see text).

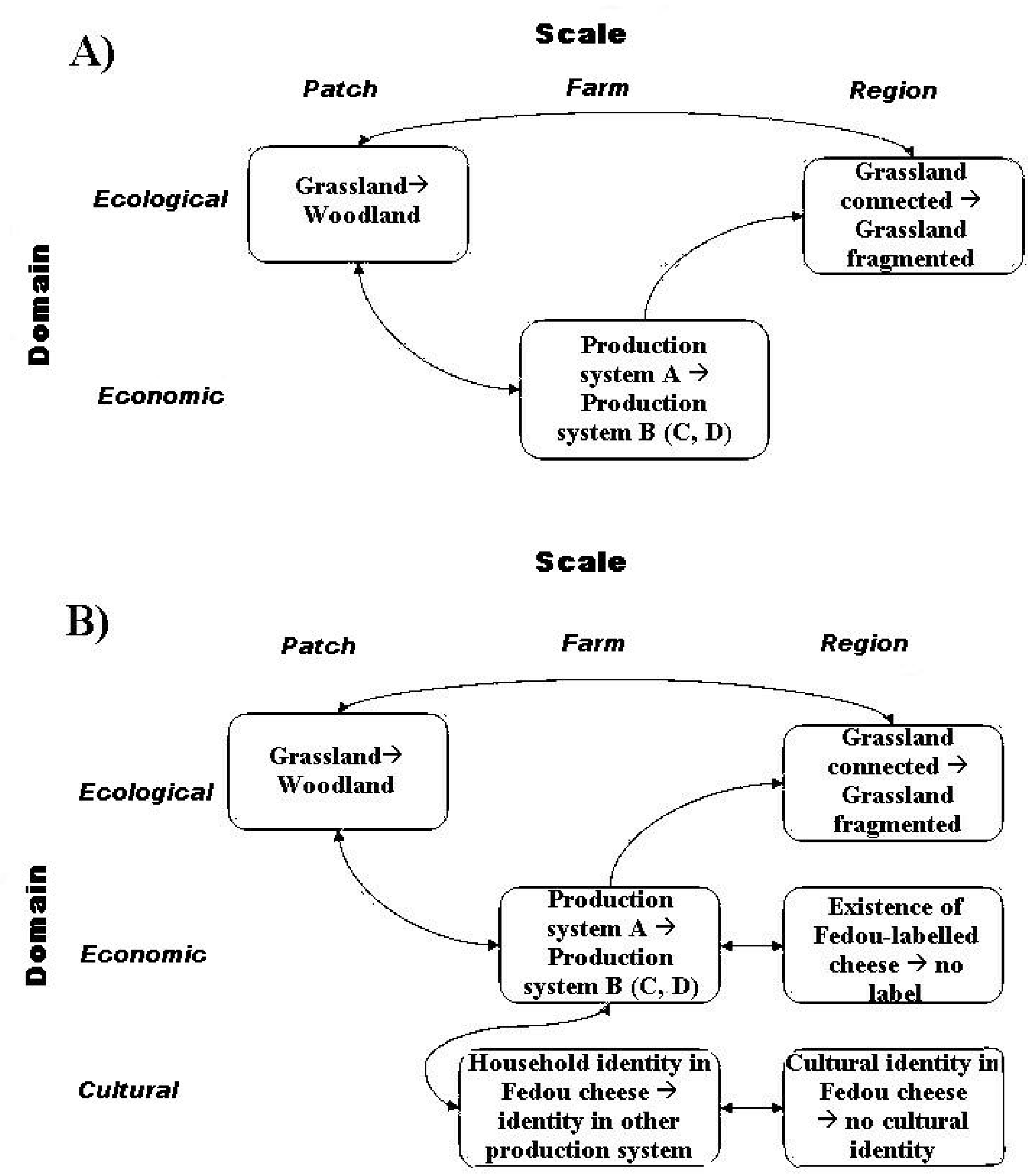


Table 1. Thresholds operating in the Causse Méjan case.

Domain	Plot level	Farm level	Region level
Ecological	Pine seed rain	Woodland (%)	Grassland area and patchiness
Sociological	Grazing and tree cutting practices	Feeding system	Labeled products
Economic	...	Farming system	Production system

tables 30–50 m below the surface. When native plants were replaced by shallow-rooted annual crops and pastures, "leakage" to the water table increased by 8–10 times (Anderies 2005), causing water tables to rise over many decades to within a few meters of the surface. Water tables now reach the surface over progressively larger areas with each succeeding wet period. The rate of water table rise is exacerbated by the application of irrigation water.

Water table rise causes waterlogging and can induce salinization. Salt, imported into the catchment via rainfall over millennia, is stored in the soil profile below the rooting zone of the native vegetation, i.e., the average depth of rainfall penetration. As water tables rise, the salt dissolves into solution and is mobilized upward. In locations in which water tables have moved to within 2 m of the surface, capillary action draws water to the soil surface where it evaporates, accumulating salt in the upper soil layers.

Horticultural crops are more sensitive to waterlogging and to salt concentrations than are dairy pastures. Pastures can persist with water tables as shallow as 40 cm, provided that irrigation is continually flushing salt down through the soil profile. Irrigated pastures require much more water than irrigated horticulture. Water costs are relatively small in horticulture but are a major part of the costs in dairy farming. Dairy farming requires either irrigated pastures or purchased fodder, which is more costly and therefore not viable for farms at the lower end of profitability.

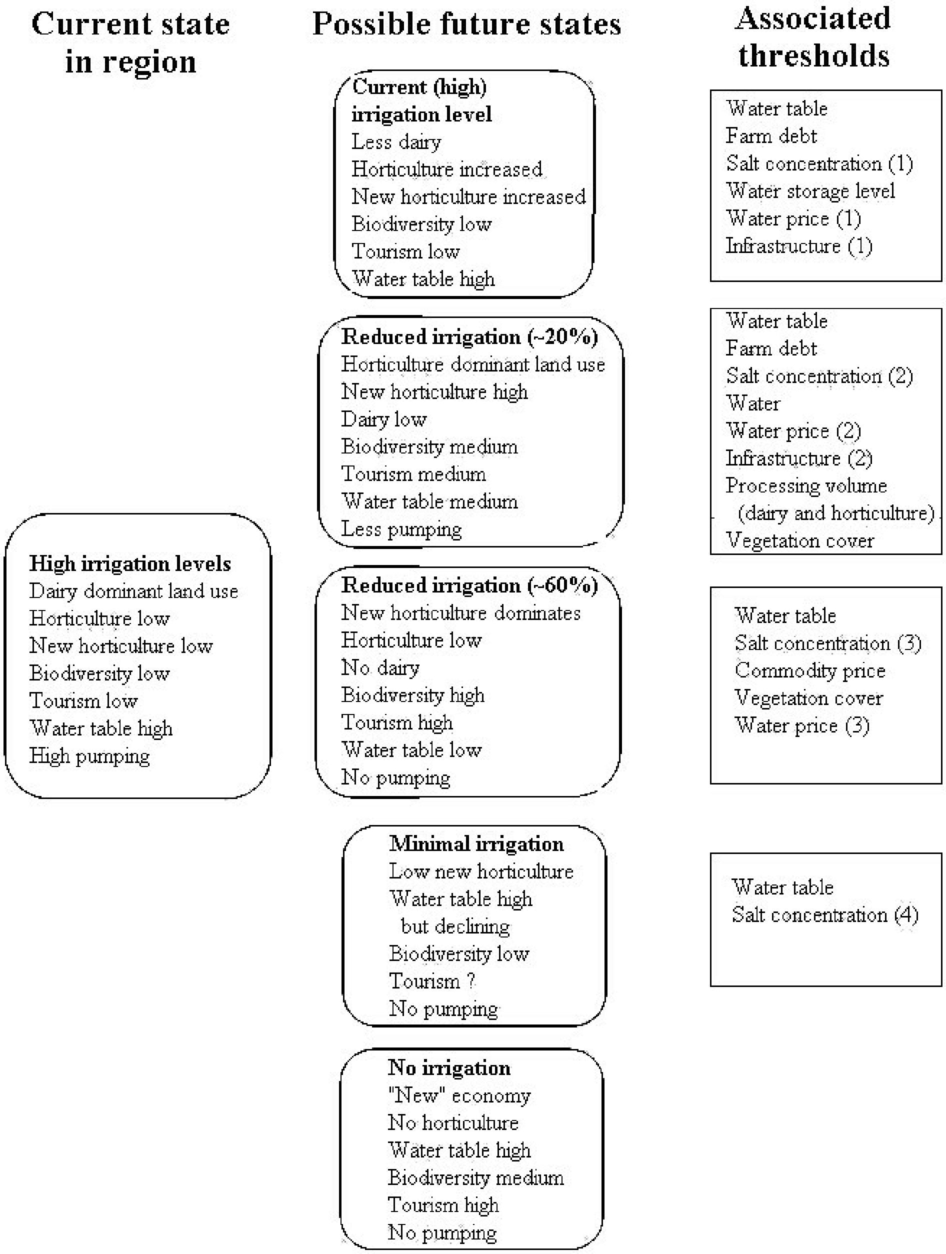
To combat rising water tables, continuous groundwater pumping has so far been able to keep the water table below 2 m. However, pumping is limited to areas with suitable soil types, which currently comprise less than 40% of the region and are focused around the horticultural areas. Pumped salty water is disposed of via drains into the Murray River, but, to protect downstream water users, there is a cap on the amount of salt that can be exported. Any excess must be discharged into evaporation pans in the catchment.

System dynamics, thresholds, and drivers

Figure 4 outlines the current and possible future regimes for the irrigation region, the current one being "high irrigation, high pumping," and associated levels of various land uses. We then identify a number of possible future regimes to which the system could move. The key drivers are rainfall, which is expressed as water storage level; the salt cap; water prices; and societal demands for water. The final column in Fig. 4 identifies the possible thresholds that, if crossed, will bring about a shift from the corresponding regime to one of the other regimes. In this set of threshold "boxes," some thresholds are followed by a number in parentheses. These represent successive levels on the same controlling variable marking different threshold effects, i.e., different magnitudes or kinds of feedback effects.

In all, we identify nine possible thresholds on key controlling variables. As the options for possible future regimes diminish because of irreversible shifts, the number of remaining operational thresholds gets smaller. In the "minimal irrigation" regime, only two thresholds are operative, with the

Fig. 4. Current and possible future states in the lower Goulburn-Broken Catchment and the associated thresholds. The numbers in parentheses in the boxes for associated thresholds represent successive levels on the same controlling variable marking different threshold effects, i.e., different magnitudes or kinds of feedback effects.



highest salinity one marking the end of any crop production. Crossing this “salt concentration” threshold results in a regime shift that excludes all cropping and hence moves the system to the final “no irrigation” regime.

Although each regime shift is significant in its own right, it is the interactions among threshold effects that introduce uncertainty and create potentially larger shocks to the system.

Threshold interactions

The significance of the interactive effects of thresholds is best illustrated by considering the possible regime shifts under a change in one key driver, rainfall, with other drivers remaining more or less at their present levels.

A heavy rainfall period similar to those experienced twice during the last 50 yr leads to a regime shift at the patch scale in the ecological domain, as shown in Fig. 5A, and the patch ceases to be well drained and nonsalinized and becomes waterlogged and salinized. The change in feedbacks involves reduced plant growth and transpiration, thereby maintaining the patch in the waterlogged, saline regime. If enough patches undergo this regime shift, the farm itself crosses an economic threshold, with insufficient arable soil to sustain a viable agricultural enterprise. Increased pumping can offset the rising water tables up to a point, but if the rate of water level rise exceeds the maximum rate of extraction by pumping, which is determined by soil type, waterlogging is inevitable. A patch-level ecological regime shift leads to a farm-level economic shift, much like the Causse Méjan case study.

Native vegetation is also killed by both waterlogging and salinity, and, as more patches shift from well drained/nonsaline to waterlogged/saline, total vegetation cover declines. When it drops below ~ 30%, the loss of ecological connectivity between patches for animal species movements causes a marked change in the persistence of many species. This gives rise to a regional-scale ecological threshold in vegetation cover.

During drought, a disturbance at the other end of the rainfall spectrum, stores of irrigation water continue to decline. Farmers have historically, and optimistically, determined entitlement “rights” to particular water allocations. If stores fall below the threshold at which there is enough water to fulfill each farmer’s annual entitlement, farmers are allocated only a percentage of their entitlements. They can also buy more water on an open market if it is available. The immediate change in feedbacks is a significant increase in the price of water. Some farmers choose to sell their allocations rather than struggle with the reduced supply. As discussed earlier, increased water prices affect dairy farmers more than horticulturalists. This is shown in Fig. 5B.

Drought also affects the infrastructure of the irrigation system. Privatization of the irrigation system in the mid-1990s created a new threshold for maintenance costs. The water management authority can generate the profits needed to cover expenses related to system maintenance only when excess water is available for sale. As maintenance costs increase, there comes a point at which the required investment in maintenance exceeds the expected future returns from irrigation, and those parts of the irrigation canal system are then abandoned.

The high vs. low rainfall “shocks” illustrate the interactions between thresholds at different scales and across different domains in response to the influence of changes in a key driver. The first threshold to be crossed depends on which condition, i.e., a drought, or an above-average wet period, occurs first or persists longest. We show all the threshold interactions in Fig. 5C.

The regional-scale economic threshold box for the GBC includes thresholds for the volumes of milk and fruit available to support viable local processing industries for these two commodities. Below some threshold levels, the processing plants become nonviable and close down, and the feedbacks from this involve increased transportation costs for farmers. Crossing either the farm-scale viability threshold induced by drought or the one induced by a prolonged wet period causes these regional-scale processing-volume thresholds to be crossed. One of the three dairy processing plants in the GBC did, in fact, close down in 2005.

The final regional-scale social threshold we consider marks a shift from a regime in which societal demand for irrigated agriculture, and therefore for water to be used for this purpose, is dominant over the demand for environmental flows and nature conservation. Such a threshold or "tipping point," as such an event is often referred to in social systems, would also likely involve a change in the amount of salt the region is allowed to dump into the Murray River via pumped salty groundwater, i.e., the salt cap. Farmers have little influence over this, and it can change rapidly depending on political dynamics.

The environmental flows vs. agriculture issue is an example in which social influence can change the position of a threshold. In other words, rather than the system moving slowly toward a threshold, as in the case of groundwater rise or salt concentrations, here a social process can suddenly move the threshold itself, causing a regime shift in the availability of water for irrigation or from current pumping levels to no or significantly less pumping.

Finally, referring back to the regional-scale ecological threshold, the collapse of the current irrigation industry and consequent development of new land uses could see an expansion of vegetation cover, moving the system toward the critical 30% threshold for increased species survival.

Concluding remarks

Most of the identified thresholds are unlikely, on their own, to fundamentally change the trajectory of this system. However, crossing a threshold at one scale in one domain can influence the dynamics of the system with regard to thresholds at other scales. The combined effect of such multiple regime shifts could well be a change in trajectory to one in which irrigated agriculture plays only a minor or no part in the future of the lower GBC.

The wet- vs. dry-period disturbances raise an important point about reversibility in threshold dynamics. A salinity regime shift is, for all practical purposes, irreversible. The waterlogging effect on its own is not. The farm viability shift is irreversible for the individual, but for the system as a whole, new players can come into the system and buy the farm. The infrastructure shift is irreversible unless economic conditions greatly improve. The biodiversity threshold crossing is reversible. Given this, the cascade of likely threshold crossings under a wet-period disturbance is likely to induce a more permanent and costly change in state (as depicted in Fig. 5). This puts more emphasis on the resilience of the system to salinity than to some of the other possible shifts.

THE WESTERN AUSTRALIAN WHEATBELT

The case study of the western Australian wheatbelt (WAW) is similar to the Goulburn-Broken Catchment example in that human activity has irreversibly changed the hydrological cycle. It is also different in that irrigation has not been a contributing factor, and the sole cause is the extensive removal of native vegetation and its replacement by cereal broad-acre dryland farming and sheep production. Otherwise, the salinization processes are similar to those described above. However, the context is quite different, because a number of factors limit alternative trajectories, such as water supply, infrastructure, demographics, and distances to markets.

System dynamics, thresholds, and drivers

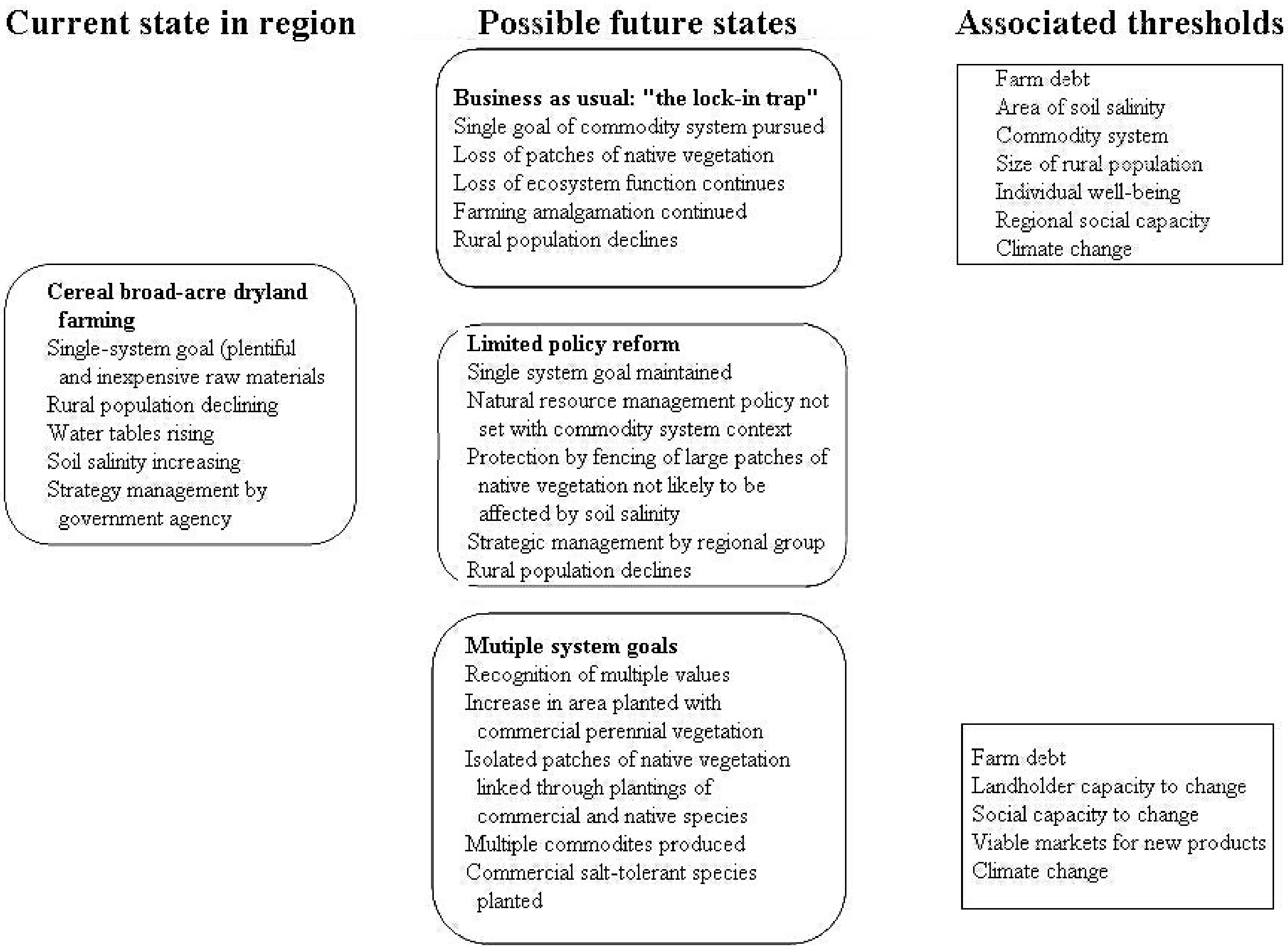
Prior to European settlement, Aboriginal society influenced the western Australian landscape for between 60,000 and 140,000 yr (White 1994). Since British settlement in the early 1800s, the region has been changed successively from a system with high biological diversity dominated by perennial native vegetation, mainly savanna shrubland, to one dominated by annual cropping systems. Less than 10% of the original area of native vegetation remains.

Figure 6 describes the current and three possible future states for the WAW, influenced by seven kinds of thresholds: the commodity system, farm debt, area of soil salinity, size of rural population, individual well-being, social capacity, and climate change.

The current state is characterized economically by the production of wheat. The success of wheat, however, has resulted in a rise in water tables in many areas, and soil salinity is increasingly affecting not only agricultural productivity but also infrastructure such as roads and buildings. In addition, salinization affects native vegetation, which also suffers declines because of grazing and pest invasions, exacerbating the hydrological imbalance (Saunders et al. 2003).

Since the 1960s, there has been a decline in the human population, and the future survival of many rural towns appears to be in doubt. We acknowledge that the reinforcing feedback loops of the

Fig. 6. The current and possible future states in the western Australian wheatbelt and some of the key thresholds.



commodity system that extend from the global scale to the individual farmer are the fundamental driving forces that produce the region’s dynamics. In this section, however, we are interested in the internal controls and feedbacks at the regional level that define the responses within this larger context.

In the early 1900s, only a few years after the WAW was first cleared for agriculture, the first areas of land rendered unproductive because of flooding and soil salinity began to appear. By 2000, 16% of the land had become saline and was largely unproductive for commercial agriculture (National Land and Water Resources Audit 2001). It is predicted that a new hydrological equilibrium affecting 33% of the land will be reached between 2030 and 2050 in some areas in the western edge of the WAW, while in the eastern parts of the region it may take as long as 300 yr to reach equilibrium (Hodgson et al. 2004). This process appears to be irreversible. The prediction that 33% of land will become unproductive is based solely on the effects of salinity and does not include any other forms of land-degrading processes that may partially reduce soil fertility, such as acidification, sodicity, and erosion (National Land and Water Resources Audit 2002).

At the regional scale, the regime shift from productive to degraded land caused by soil salinity is a slowly emerging biophysical process considered to be irreversible. There is a time delay between the direct cause and the effect, that is, between land clearing and the resulting inundation and soil salinity. Temporal separation between cause and effect has been reported to contribute to the intractable nature of natural resource problems (Meadows and Robinson 1985). Recently, some land-use change from cropland to commercial forestry has occurred, in part as an attempt to combat the hydrological imbalance, although this represents only a very small proportion of the total land area and is mostly in areas with annual rainfall greater than 600 mm. Such efforts are unlikely to salvage large areas that are or will become salt-affected.

Land clearing and increasing soil salinity further impact the remaining native vegetation and freshwater ecosystem with a reinforcing feedback loop. Many patches of native vegetation have reached a critical threshold at which they are isolated from each other, thus contributing to their degradation and a reduction in the populations of native animals and birds. In addition, most freshwater ecosystems are now saline because the water tables have crossed a critical threshold.

In the 1970s, a change in the socioeconomic regime from expansion to consolidation and amalgamation of farms and increasing land and water degradation led to the crossing of a critical threshold in the sociocultural domain. The number of farming enterprises peaked in the late 1960s at around 23,000, but has fallen sharply from then until, in 2003, there were just over 8000 farming enterprises, with an annual decline of about 7%. In recent times, a lack of large areas of native vegetation available for conversion to cropland has made it impossible for farms to expand by clearing more land. Consequently, the need for efficiencies of scale has resulted in farm consolidation (Mackenzie 2004). Compounding this process are terms of trade that are increasingly unfavorable to the farmer; these affect farm viability and increase farm debt. As a result, families are leaving the industry, with a consequent reduction in the numbers of people in the rural landscape. There are thresholds in population size below which towns become unviable when local services such as health care and schools are withdrawn, further reducing the population. The cascading effect of farm amalgamation is to reduce the populations in towns, threatening the survival of many rural communities.

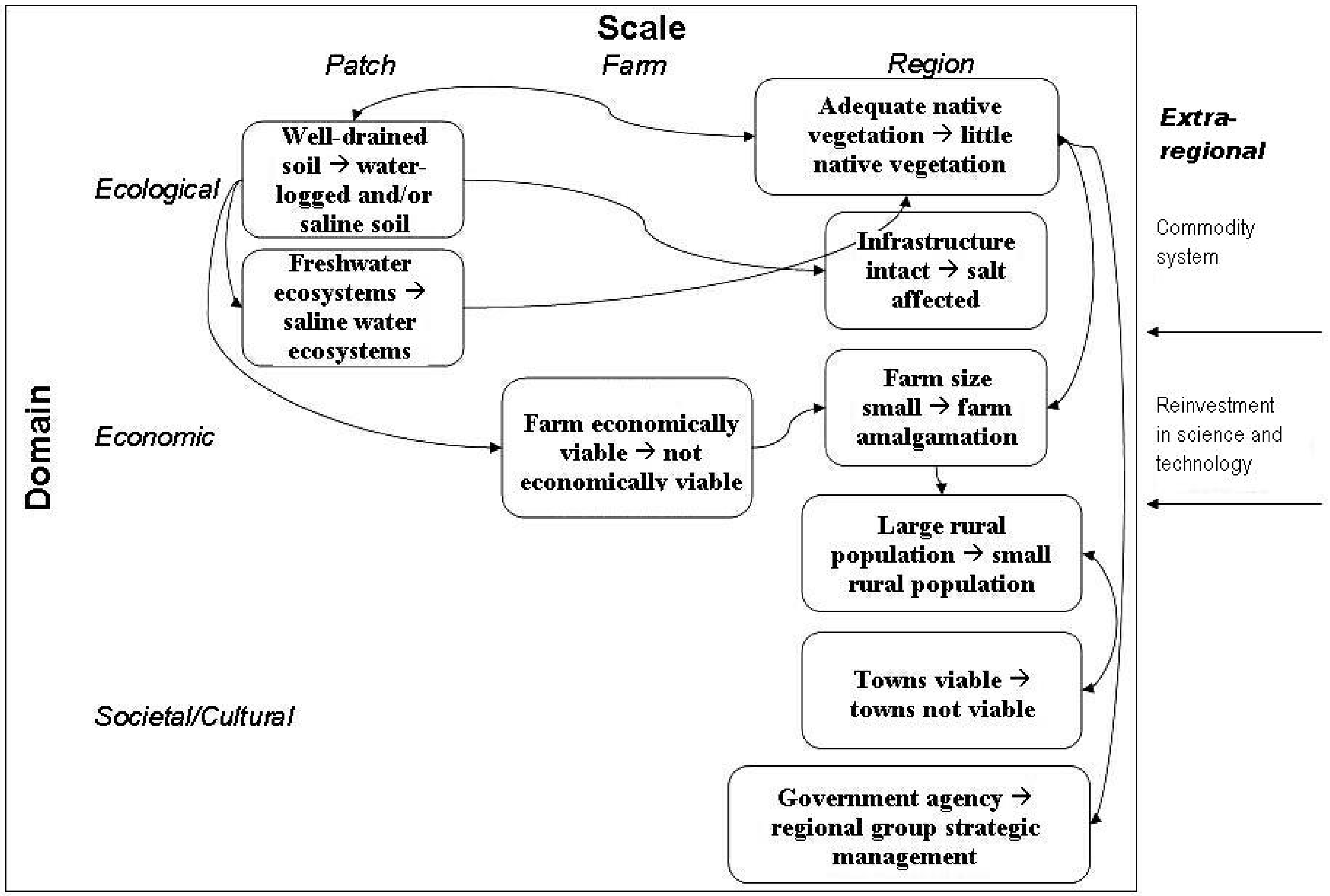
The effect of the slowly emerging soil salinity problems influenced regional land management policy. During most of the 20th century, the sociocultural domain in the region was dominated by the command-and-control policy and strategy of government agencies. However, a growing awareness of land degradation problems and increasing dissatisfaction with the agricultural statutes and policies intended to manage those problems led to deregulation and the development of nonstatutory policy that emerged in the 1980s to address broader environmental goals. These took the form of a shift toward integrated approaches to land management policy delivered through partnerships with community groups and four state government agencies responsible for natural resource management.

There was a regime shift from the command-and-control policy toward partnership approaches in which community groups were strongly influenced by national policy. Here we see a change in the internal rules, i.e., the controls and feedbacks, of society at the regional scale that led to an ever increasing problem of land and water degradation that was unresponsive to the previous command-and-control regime. These interacting regime shifts are shown in Fig. 7.

Possible future states

Three possible future states are shown in Fig 6. Each is described in minimal terms by its configuration and key attributes. The key drivers include the level of farm debt, the extent of soil salinity, the type of commodity system, the size of the rural population, individual well-being, regional social capacity, climate change, individual capacity to change, and the creation of viable markets for new products. In the limited policy reform state, it is suggested that larger areas of native vegetation can be protected and conserved by fencing and linked to each other through strategic plantings of native and/or commercial species to maintain biodiversity and ecological services. This will require increased societal appreciation of the benefits of ecosystem services to increase the demand. The rural population will continue to decline because of farm amalgamation, and it is not known at what level the

Fig. 7. The key threshold interactions in the western Australian wheatbelt in the three domains and at three scales. Note that there are also forces operating at the global scale, notably the availability of new technologies, climate change, and the global demand for cereal products.



population will stabilize. The cascading effect of the declining rural population on both individual and regional social capacity is now being realized (Shrapnel 2001). For example, the suicide rate in rural Australia is alarming. In previous decades, farmers who stopped farming could find employment in nearby towns. Opportunities to live and work in rural areas, however, have diminished, causing high levels of stress. This cascades to a weakening of the rural social fabric, hastening further depopulation.

A third possible future state, in addition to the “business as usual” state, is called “multiple system goals.” This state is marked by a shift in which society recognizes and values ecosystem services, nature conservation, and biodiversity. Larger areas are planted with commercial perennial species such as oil mallees, which produce activated carbon for renewable energy and eucalyptus oil. If these plantings are extensive enough, they may potentially alter the rate of change in the hydrological cycle at the farm scale. However, this would require the creation of new markets for these products to achieve economic viability. An expansion in vegetation cover as envisioned by innovative revegetation projects such as Gondwana Link (Wilderness Society 2005) may help to increase the vegetation cover toward a critical threshold of vegetation connectivity and vegetation corridors that would help restore degraded and fragmented ecosystems in the region for increased species survival. Gondwana Link has the ambitious goal of linking the dry inland areas with the wetter southwest of western Australia across an area more than 1000 km in length.

Concluding remarks

At the local scale, there has been an irreversible regime shift in land use from productive agricultural land to 16% nonproductive land affected by soil salinity. The WAW, however, continues to produce plentiful and inexpensive raw materials. It is probable that commodity production will continue to be maintained by cross-scale interactions on the individual, local, regional, and global scales and among the ecological, social, and economic domains, even in the event that 33% of the area is degraded by soil salinity.

The linked social-ecological system has not in itself experienced a profound regime shift as yet, despite a significant decline in population numbers. The viability of the region has been maintained by increased efficiency through farm amalgamation. This, of course, is at the cost of individual viability, which is an irreversible loss for the individual in most cases. Human innovation in the technical domain at the global scale and through regional restructuring has extended the threshold outward, preventing a catastrophic collapse of the linked social-ecological system at the regional scale. In many parts of the region, the loss of biodiversity is becoming irreversible as many of the smaller patches of native vegetation disappear from the landscape.

The evidence in this case study supports the central points of this paper, which are that crossing a single threshold between regimes often leads to a cascading effect in which multiple thresholds are breached and that the regime that this cascading effect ultimately produces has a tendency to be highly resistant to management strategies that seek to restore the earlier regime (see Fig. 7).

MADAGASCAR DRY FORESTS

The Androy region in southern Madagascar is today a rural social-ecological system in which numerous agricultural fields planted with maize, beans, sweet potatoes, and cassava are mixed with pastures and forest habitats on ancient sand dunes. The area is part of the “dry spiny ecoregion” characterized by semi-arid climatic conditions and levels of plant endemism that are among the highest in Madagascar. The average human population density is approximately 150 persons/km², and the urban center of Ambovombe has more than 30,000 inhabitants. Originally, the landscape of this region was mostly covered by dry forest, but forest cover has been declining since the arrival of humans in the 10th and 11th centuries. Forest cover is now severely fragmented, with several hundred forest patches < 1–95 ha in size constituting islands in a sea of agriculture. Most of these patches are protected by local taboos that restrict entrance and resource extraction. Several species of cultivated legumes, e.g., *Vigna sinensis, Phaseolus lunatus,* and *Voandzeia subterranean*, represent an important source of revenue and also an essential protein source. Crop yields of these legumes are higher when they are pollinated by insects, whose abundance and diversity increase with proximity to native forests. Further, some forest patches are protected as sites for keeping beehives for the semi-domesticated *Apis mellifera unicolor.*

The traditional belief system and informal institutions are showing a tendency to erode because of drivers such as urbanization and migration, cultural changes, and increased aridity. The region has experienced declining precipitation since the 1970s and recurrent drought conditions since 1981, with severe droughts in southern Madagascar reported in 1981, 1988, 1990, 1992, 2000, and 2003. The most severe drought in 1981 affected 1 x 10^6 people. As a response to the periods of drought, migration to areas outside Androy has increased during the last decades, and these drivers have started to affect the enforcement of local protection of the forest patches.

Modeling forest patch loss and pollination services

Using a model of the sequential loss of forest patches that starts with the ones with the weakest protection and eventually encompasses even the most sacred forests, Bodin et al. (2006) calculated the area covered by pollination services based on a range of foraging distances for pollinators. In spite of the current fragmented nature of the landscape, the results indicate that the fraction of the landscape presently covered by crop pollination services is surprisingly high. For example, crop pollination services cover almost half of the landscape even in the lowest part of the estimated foraging range. However, irrespective of assumptions of foraging distances (Fig. 8), a very rapid decline in the total crop pollination area occurs when patches ≤ 5 ha are removed. At a foraging distance of 400 m, the remaining pollination cover is reduced to 12% of the original area and, at 1400 m, to approximately 50% of the original area (Bodin et al. 2006). The rapid decline in ecosystem services in response to patch removal was generated by changes in the spatial configuration of the patches rather than the reduction of area per se. It has often been emphasized that, when fragmentation results in less than 30% of a specific habitat type on a landscape, the spatial arrangement of patches becomes more important for species survival than does total habitat area (Andrén 1994).

Potential thresholds and regime shifts

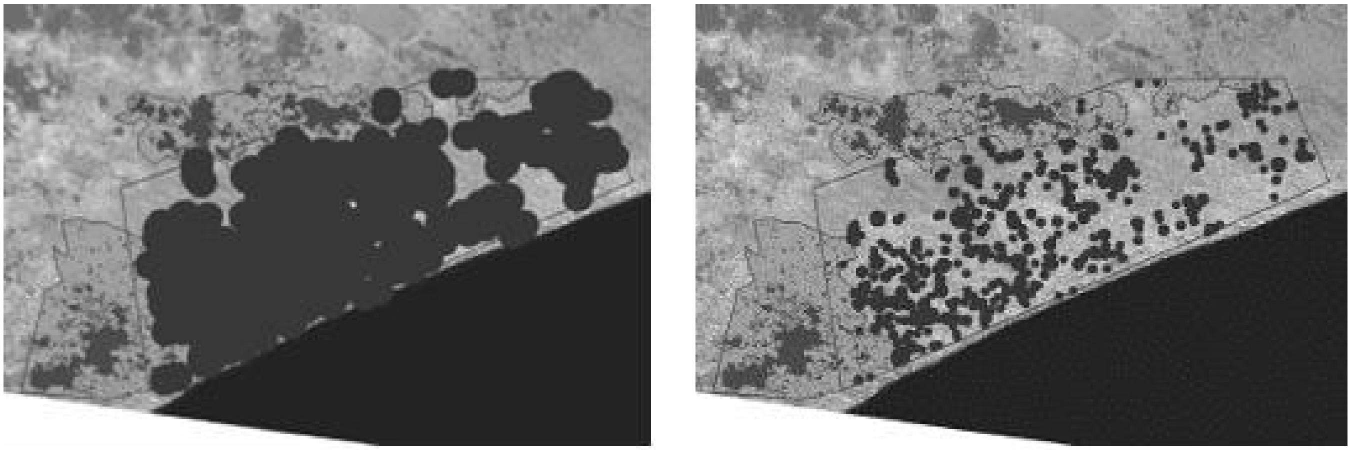
Even if the loss of forest is restricted to the smallest patches, this has potentially severe economic consequences for insect-pollinated crops and the regional economy. Traditional honey production is also affected by forest patch loss. Furthermore, the loss of forest cover decreases sand dune binding and wind breaks (a linear relationship), thus further affecting agriculture.

In Fig. 9 we have listed features of the Androy social-ecological system, i.e., characteristics of the current states and potential future states. Factors influencing the future state of the social-ecological system include climate change, demographic changes, and changes in property rights regimes. The current state is characterized by a high degree of local protection of forest patches, and, according to our analyses, ecosystem services such as pollination are in a fairly good state. However, the culturally based protection system is slowly eroding, leading to a loss of forest patches and ecosystem services. Alternatively, the government may intervene and institute formal protection of large forest patches. Such a scheme is linked to major policy shifts that have recently been introduced in Madagascar for the purposes of increasing the protected area estate from 1.7 x 10^6 to 6 x 10^6 ha, some 10% of the land area, over the next 5 yr. However, any government protection scheme will likely focus on the large forest patches (> 50 ha), and the small patches will disappear even under this scenario, with a resulting loss of ecosystem services. A third state is reinforcement of local informal protection and the development of co-management systems that could help maintain and restore existing forest patches. However, this state is still vulnerable if poverty remains widespread. The fourth potential state represents a local collapse because of increased frequency of drought, in which case a large-scale migration and abandonment can be expected. The result may be either a slow regeneration of forest because of the reduced human presence and impact, or a rapid deforestation of the remaining forest if local property rights collapse and outsiders invade to extract the forest resources.

Here, too, we see the potential for threshold interactions that might alter assessments of future scenarios. One might initially suppose that the cultural pressures to retain sacred forests would ensure pollinator habitat and farm viability. However, consider the possibility that farms might fail because of, for instance, climate change and increasing aridity. As more and more farms cross a threshold of viability, out-migration will increase. In addition, out-migration and changes in agricultural viability may alter the regional economy and its connections to a global trading regime. Both of these may serve to erode the cultural protection for sacred forests. Fragmentation of the remaining forests would increase, and patch-level pollination would decline to a point at which some patches would receive insufficient pollination services. This in turn would lead to an increase in the number of failing farms. These threshold interactions are shown in Fig. 10.

In summary, to reduce the risk of abrupt changes in agricultural viability in this area, small forest patches should increasingly be viewed as essential components in the production landscape. However, to avoid passing the ecological thresholds it is also necessary to avoid passing sociocultural thresholds, and new institutions and relevant policy instruments are needed to reinforce or replace eroding informal institutions that no longer adequately address the management of the small, but important, landscape habitats.

Fig. 8. Images showing crop pollination areas, i.e., the area being serviced by pollinating bees based on forest patches ≥ 1 ha in the Madagascar case study. On the left, the area is serviced under the assumption that the distance within which most pollinator foraging occurs is set to 1400 m. On the right, the area is serviced with much more restricted foraging of < 400 m (see Bodin et al. 2006).



SYNTHESIS

The four social-ecological systems described in this paper are all very different in terms of their ecological features, the social and cultural features of the human inhabitants, their production systems, and histories. Nevertheless, they show a remarkable similarity when viewed in terms of the kinds of dynamics they have exhibited and the mechanisms that determine their possible future trajectories.

Two significant features of social-ecological systems emerge from this analysis:

1. Considered in their entirety, social-ecological systems have multiple threshold effects associated with a number of different controlling, slow, variables that operate at different spatial and temporal scales and in different domains. These thresholds define multiple possible regime shifts that collectively determine possible alternative regimes for the social-ecological system. Although the resilience of each of these regimes differs considerably, they nevertheless constitute different self-organizing configurations.
2. The crossing of one threshold frequently induces a cascade effect that ultimately leads to the breaching of one or more additional thresholds. The greater the number of thresholds crossed, the more likely it is that one or more will be effectively irreversible. Thus, cascading regime shifts are more likely to lead to highly resilient new regimes and effectively irreversible changes. These cascading regime shifts cross domains and scales. Managers focused too strongly on one domain or one scale are likely to miss the possibility for interactions among regime shifts and the likelihood that a new, resilient, and possibly less desirable system will emerge.

The four case studies taken together provide an illustration of the general model of threshold interactions in social-ecological systems that we presented at the start in Fig. 2. All showed essential domain/scale thresholds in similar positions on the matrix, e.g., patch-level ecological thresholds or regional sociocultural thresholds. In some ways, this is not surprising. A farm is, after all, an economic or social designation, and thus we would not expect ecological thresholds to necessarily operate there,

Fig. 9. The current and possible future states in the Madagascar dry forest region and some of the key thresholds.

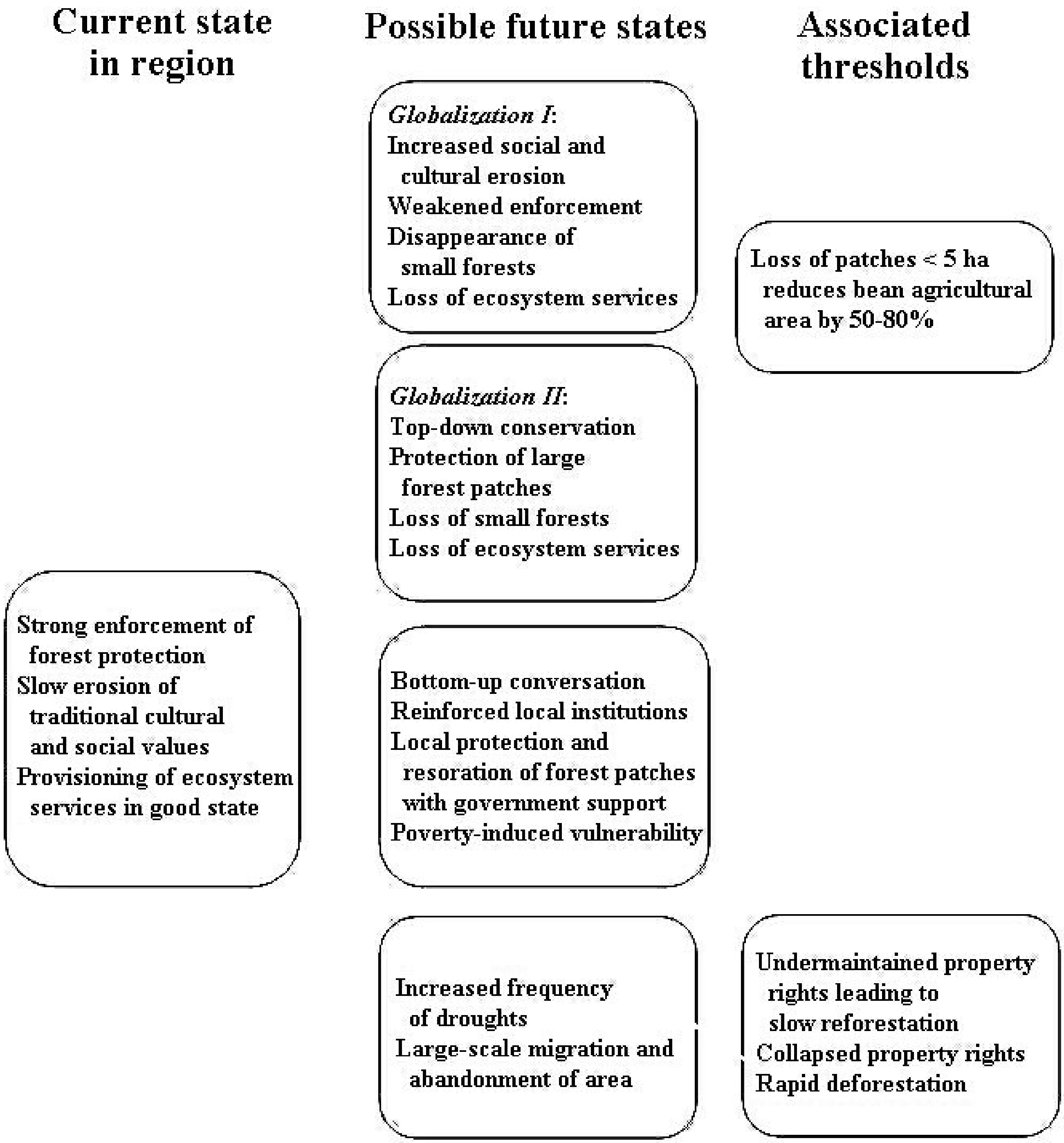
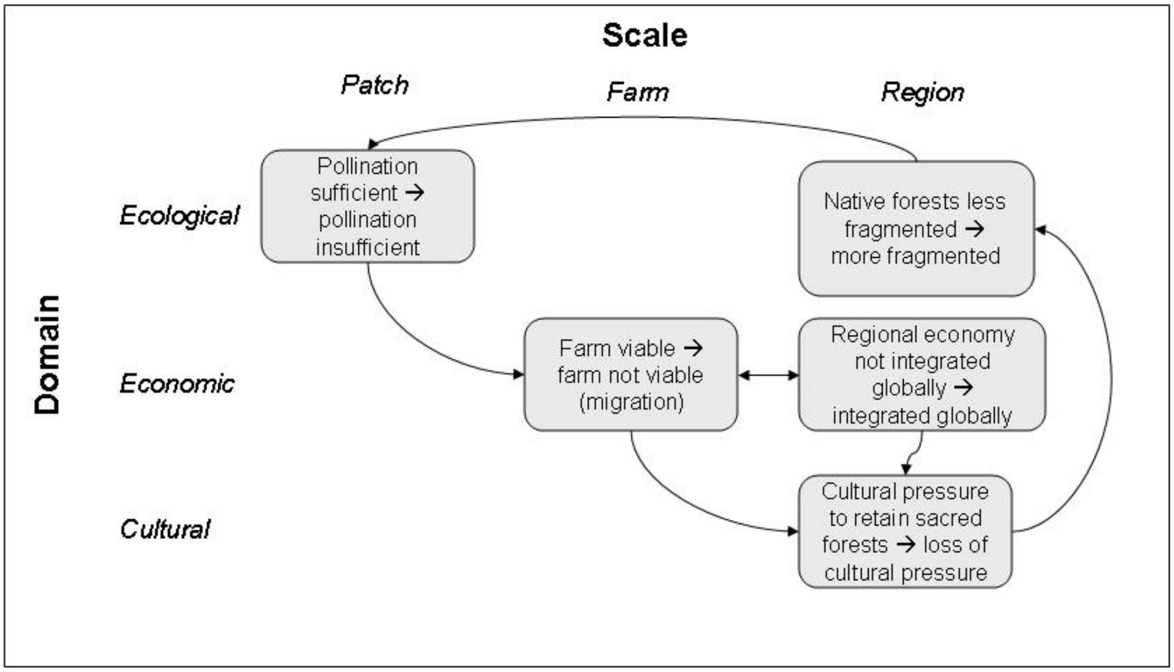


Fig. 10. The key threshold interactions in the Madagascar dry forest case in the three domains and at three scales.



although they may be forced, as they are in some of the cases, by the human structuring of the landscape on the farm scale. Similarly, we are used to thinking about cultural and social forces on scales larger than a patch.

What is surprising is the seeming generality of the interactions between thresholds. The solid lines in Fig. 2 indicate interactions that were important in all cases. The dotted lines indicate thresholds that were important in one or two of the cases. Both give some guidance. Interactions between ecological and economic thresholds at different scales must be analyzed and understood by any manager trying to influence a regional social-ecological system. Otherwise, policies designed to create a particular future state may backfire as multiple thresholds are breached. Equally importantly, however, sociocultural thresholds cannot be overlooked. We assert that they frequently are; natural resource managers take them, and the constraints and opportunities they visit on the system, as a given. However, if they give way to a new sociocultural regime, there can be profound repercussions in the system; witness, for instance, both the Causse Méjan and Madagascar case studies.

Of course, all regional social-ecological systems are also affected by extra-regional, including global, forces, as emphasized in the western Australia case study. Analyzing those in detail was beyond the scope of the case studies presented here. In large part, these are forces that regional managers are unable to control and that must just be taken as constraints upon the system. Nevertheless, a full-fledged analysis of management options and the impacts of cascading regime shifts would have to acknowledge that some regime shifts within the regional system may be precipitated by dynamics outside of the regional system. Knowing which of the internal regime shifts may be most susceptible to outside forces can aid in the analysis of which thresholds are likely to be breached first, and therefore what cascading regime shifts and eventual future states can be expected.

In each case, some understanding of the ways in which thresholds interact will be essential. There is not yet a systematic approach to dealing with threshold interactions. Our main purpose in this paper was to highlight the need to consider threshold interactions and give some indication of the domains and scales at which the most critical threshold interactions are likely to occur. Further work is needed to (1) see how universal Fig. 2 might be and (2) systematize the approach to evaluating the interactions. Clearly, formal modeling will be important in this regard and should be pursued in subsequent work on this topic. In particular, formal modeling could be used to explore the generality of Fig. 2 and to determine how often cascading thresholds lead to more or less resilient final regimes. Regardless, it seems evident that concentrating on hysteresis or threshold effects in a single domain at a single scale is likely to be grossly misleading with respect to the dynamics of the system or its future trajectories. Multiple methods, both quantitative and qualitative, will be required to envision the effects of cascading thresholds on regime shifts and resilience.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol11/iss1/art20/responses/

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