Learning from episodes of degradation and recovery in variable Australian rangelands

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Land-change science emphasizes the intimate linkages between the human and environmental components of land management systems. Recent theoretical developments in drylands identify a small set of key principles that can guide the understanding of these linkages. Using these principles, a detailed study of seven major degradation episodes over the past century in Australian grazed rangelands was reanalyzed to show a common set of events: (*i*) good climatic and economic conditions for a period, leading to local and regional social responses of increasing stocking rates, setting the preconditions for rapid environmental collapse, followed by (*ii*) a major drought coupled with a fall in the market making destocking financially unattractive, further exacerbating the pressure on the environment; then (*iii*) permanent or temporary declines in grazing productivity, depending on follow-up seasons coupled again with market and social conditions. The analysis supports recent theoretical developments but shows that the establishment of environmental knowledge that is strictly local may be insufficient on its own for sustainable management. Learning systems based in a wider community are needed that combine local knowledge, formal research, and institutional support. It also illustrates how natural variability in the state of both ecological and social systems can interact to precipitate nonequilibrial change in each other, so that planning cannot be based only on average conditions. Indeed, it is this variability in both environment and social subsystems that hinders the local learning required to prevent collapse.

climate variability | desertification | dryland development paradigm | human–environment systems | local knowledge

Three-quarters of Australia's land mass is arid and semiarid rangelands, inhabited from ≈40,000 years ago by Aboriginal people with no domestic herbivores and settled by pastoralists of a mainly European heritage <200 years ago. The past century of grazing by sheep and cattle has seen many changes in environments, social systems, and policy, spread across a vast geographical region and five state jurisdictions, such that a natural experiment has occurred of management under broadly similar social and policy drivers, but with local environmental and institutional differences (1). These conditions have resulted in modest differences in historical trajectories, creating, in their response to major droughts, a unique set of "replicated" land-change events under an approximately singular social and policy context.

Land-change science over the past decade has been increasingly concerned with the interwoven nature of environmental and social changes in trajectories of regional environmental change, particularly in the context of global change (2, 3). A clear framewok is required to conceptualize and report on these increasingly complex, systemic analyses. Taking up this challenge for global drylands, Reynolds *et al.* (4) have proposed the Drylands Development Paradigm (DDP) to help analyze changes in dryland human–environmental systems. They make the case that these systems possess a unique set (or syndrome) of features (particularly climatic variability and unpredictability, low productivity, sparse populations, distant markets, and remote governance). They then argue that the five principles shown in Table 1, although also important elsewhere, are a necessary and sufficient set to structure the analysis of change in drylands. The intimate coevolution of the human and environmental subsystems [DDP principle 1 (P1)] is seen to be fundamentally modulated by the interactions between human decision making and the environment's provision of ecosystem services (Fig. 1). The DDP argues that the efficacy of these interactions is determined by local environmental knowledge (LEK).

This article reports a metaanalysis of a much larger, more comprehensive work by McKeon *et al.* (1) that used historical records, newspaper accounts, reports from Royal Commissions, government resource surveys, personal anecdotes, scientific writings, and modeling to document and summarize eight degradation episodes (seven considered here; Fig. 2) in the Australian rangelands, spread across 90 years in time and 5 million square km in space. Previous studies have reported specific cases of dryland changes [e.g., a 5,000-year history for the Negev Desert (15)], and a masterful metaanalysis of 132 diverse case studies across the world (16). The purpose of this article, however, is to reanalyze the Australian degradation episodes through the DDP principles, identify the emergent lessons for management and policy, illuminate land-change science feedback mechanisms (Fig. 1), and test the DDP analytical framework.

Context and Drivers

Australia's rangelands span a wide range of environments from arid and semiarid shrublands in southern and western Australia to tropical open woodlands in northern Australia [for more background see supporting information (SI) *Text*]. The major management issue in all these rangelands is "getting the stocking rate right," that is, managing stock numbers to maintain desirable perennial forage species given variability and changes in climate, commodity prices and costs of production, government policy, financial pressures, and technological capability (17). The seven case studies of regional (≈50,000 km^2) degradation events in different parts of Australia (Fig. 2) since the 1890s highlighted a series of consistent messages. These may be summarized in

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Abbreviations: DDP, Drylands Development Paradigm; P*n*, principle *n*; LEK, local environmental knowledge.

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Table 1. Five principles (P1–P5) for understanding change in drylands, after ref. 4, with conclusions from this study

Principle	Dryland development principles and key implications	Conclusions from drought episode analysis
P1	Human–environmental systems are coupled, dynamic, and coadapting, so that their structure, function and interrelationships change over time. Understanding dryland desertification and development issues always requires the simultaneous consideration of both human and environmental drivers, recognizing that there is no static equilibrium to aim for.	The episodes cannot be understood without analyzing the links between the human and environmental subsystems. The two subsystems have shown some coevolution in the way that human learning has caused and responded to change, although there remain dysfunctional aspects to these changes.
P2	A limited suite of slow variables are critical determinants of human–environmental system dynamics. A limited suite of critical processes and variables at any scale makes a complex problem tractable.	In early episodes, pastoralists and institutions alike were only monitoring and responding to fast variables (rainfall and pasture production, not long-term climatic cycles and pasture condition; market prices, not long-term trends and variability), and have only gradually come to focus on the underlying controlling variables.
P3	Thresholds in key slow variables define different states of human–environmental systems, often with different controlling processes; thresholds may change over time. The costs of intervention rise nonlinearly with increasing land degradation or the degree of socioeconomic dysfunction; yet high variability means great uncertainty in detecting thresholds, so managers should invoke the precautionary principle.	There were critical thresholds observable in both human and environment subsystems, management that was viable under good climatic and market conditions collapsed when both declined; the thresholds of rainfall or stock numbers at which such collapses happen were made more sensitive by the effects of antecedent management on pasture condition (and debt levels). The eventual impacts of high stock numbers, while triggered by drought, were generally a result of slow declines in the resilience of vegetation, coupled in some cases with threshold declines in soil fertility and water holding capacity.
P4	Coupled human–environmental systems are hierarchical, nested, and networked across multiple scales. Human–environmental systems must be managed at the appropriate scale; cross-scale linkages are important in this, but are often remote and weak in drylands, requiring special institutional attention.	Understanding the interplay between effects at different scales in space, time, and institutional process is crucial to future solutions. Management and learning at the individual pastoralist scale turns out to be too fine-scaled, particularly in time, while tactical responses at the national level are too ponderous (and often counterproductive). Policy needs to focus on creating a context of regional institutions and knowledge support rather than intervening directly.
P5	The maintenance of a body of up-to-date LEK is key to functional coadaptation of human–environmental systems. The development of appropriate hybrid scientific and LEK must be accelerated both for local management and regional policy.	There was no lack of LEK and learning within some individuals' lifetimes, but this was acting against many institutional and economic pressures and mismatched particularly with the time scale of variability. The climatic drivers of importance were those associated with long-term (quasi-decadal) oscillations. This cycle (≈19 years) is too short to be regarded as invariant for a manager's lifetime, but too long for one manager to build up repeated experience of changes. The necessary collective learning requires an alliance of industry, science, and public institutions and is now further hindered by climate change.

terms of common underlying drivers and the ways in which these affect key slow variables (pasture production, economic viability, and collective knowledge) through the episodes.

At the highest level, pastoral production relies on converting rainfall into forage, the ecosystem service that supports animal production. The quality and quantity of product is determined by land condition and management decision making, with tradeoffs between short- and long-term outputs. The value of that product is then determined by market prices. In seeking to explore the effects of management decision making on the capacity of the land to deliver this ecosystem service, key drivers are thus the climatic inputs, prices, and the technical understanding available to pastoralists, all of which have varied during the period of the case studies.

The Australian climate has been shown in general to be more variable than most other regions with comparable mean and seasonality of rainfall globally (e.g., ref. 18), but its important feature in the present context is the diversity of (interacting) periodicities at which this variability is expressed (19). Aside from underlying intraannual and interannual variability, the occurrence of substantial wet and dry periods is associated with the El Niño–Southern Oscillation effect on about a 4-year periodicity (1–8 years for the 27 occurrences of El Niño during 1891–1994). However, there is good evidence that the severity of these events is modulated by the Interdecadal Pacific Oscillation (1, 20, 21) with a mean periodicity of ≈19 years (SI Fig. 4), although this finding may really reflect a more complex interplay of cycles (19). In addition to these drivers, there is now clear evidence of trends in rainfall since ≈1960 (mostly increases in the northwest and decreases in the south and east of the continent) associated with climate change (22). Thus from the perspective of pastoralists, the climate system imposes an evident fast variable in the form of very dynamic annual rainfall, but it hides slower variables on time frames comparable to working lifetimes, such as bidecadal, quasi-cyclical components, and recent trends caused by climate change.

Commodity price variability provides a second driver. Both sheep and cattle pastoralists have been exposed to considerable short- to medium-term variability in real prices over the past century, and longer-term trends, mostly downward since the 1950s for wool, whereas beef rose to a peak in the 1970s before falling hugely in 1973–1974, then rising in 1979 (1) (SI Fig. 5) and again since 1998. This continental summary, driven mostly by global trends, masks further short-term variability experienced

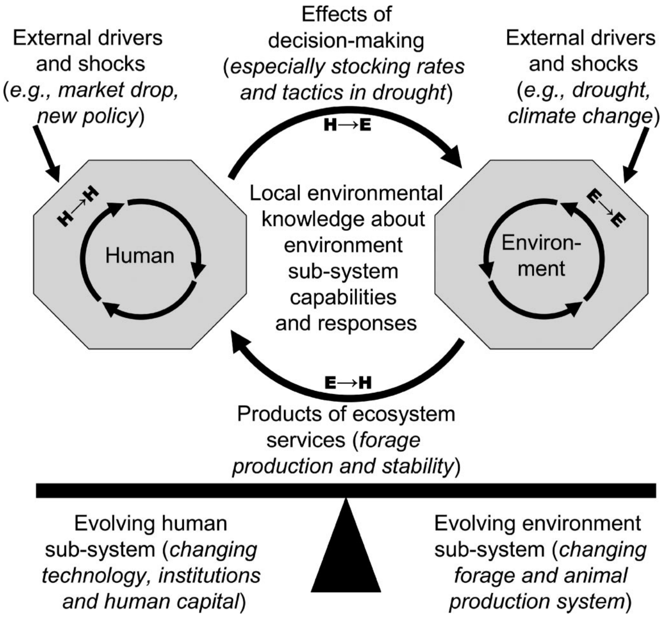


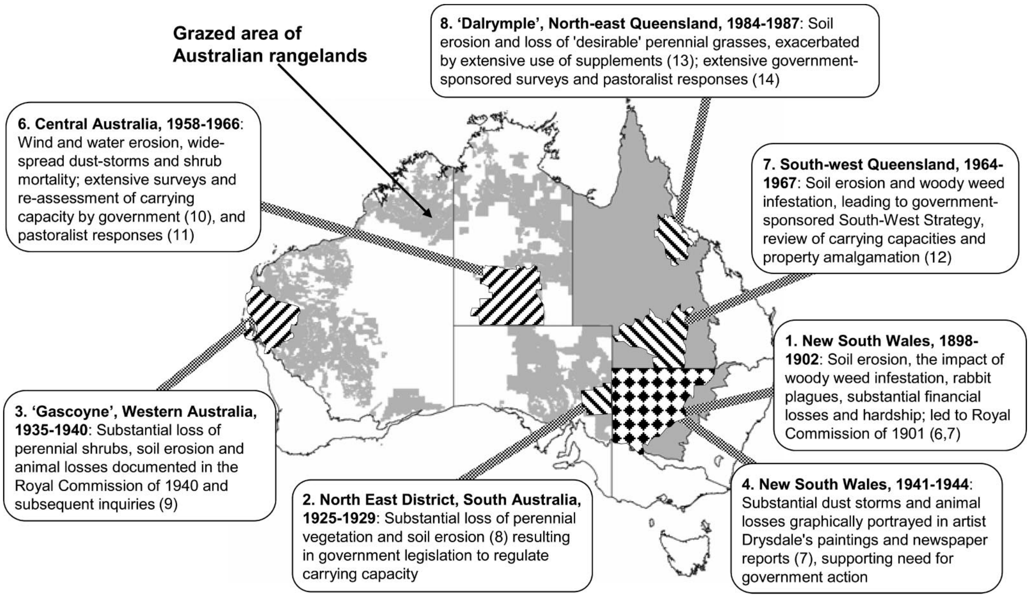
Fig. 1. Schematic of the interactions between the human and environmental components of the land system (combining concepts from figure 21.5 in ref. 5 and figure 4 in ref. 3, with specifics for this analysis in italics), showing decision making and ecosystem services as the key linkages between the components (moderated by an effective system of local and scientific knowledge), and indicating how the rates of change and the way these linkages operate must be kept broadly in balance for functional coevolution of the components.

in individual sale yards. Thus, for prices as with climate, pastoralists are exposed to unpredictable variability at all time scales up to that of a working lifetime, in patterns that are not strongly correlated with the climate.

Options for managing grazing pressure derived from a wide range of changes in technology, genetics, and social trends (for more detail see *SI Text*) constitute a third crucial driver. Grazing pressure is the ratio of forage demand from all grazers (domestic or otherwise) to forage supply and can increase under low rainfall even without changes in animal numbers. Matching animal numbers to forage supply is the critical management decision facing pastoralists everywhere. This process is relatively simple with stable forage production but risks substantial (short-term) economic and (long-term) environmental penalties if the wrong stocking rate decision is made in the face of uncertain forage supplies. Although there has been a long-term trend toward a greater understanding of rangelands production systems, a better ability to set the appropriate grazing pressure, and slowly improving incentive policies, several factors have also promoted short-term increases in grazing pressure that have turned out to have long-term disadvantages. For example, the use of supplements in northeast Queensland in the 1980s had immediate production benefits but also turned out to permit excessive grazing pressures in drought (13), an effect exacerbated by the effects of discount rates on human decision making (see *SI Text*). Thus the management options open to pastoralists, and the changing perceptions of their benefits, create further medium- and short-term variability nested within long-term trends.

Responses in Degradation Episodes

Drought was the major focus for people at the time of the episodes, and hence it is the basis for our analysis. However, in most cases the sequence of dry years, ranging from 2 to 8 years, exposed and amplified degradation processes that were already occurring (1). The evidence for degradation is unequivocal. The accounts from the time are graphic in their descriptions of the physical "horror" of bare landscapes, erosion scalds, gullies, and dust storms. Subsequent observations documented the environmental and economic damage caused by loss of palatable perennial species, "woody weed" infestation (unpalatable perennial species), and soil loss. Animal suffering through deaths or forced sales was also highlighted; for example, it was reported that >100 million sheep died in "the eight severe droughts that have affected the Australian pastoral industry since 1880" (23). Importantly from the human perspective, numerous accounts have described the financial and emotional plight of pastoralists and their families during drought, leading to abandonment of properties or, sadly, deaths (e.g., refs. 24–26).



8. 'Dalrymple', North-east Queensland, 1984-1987: Soil erosion and loss of 'desirable' perennial grasses, exacerbated by extensive use of supplements (13); extensive government-sponsored surveys and pastoralist responses (14)

6. Central Australia, 1958-1966: Wind and water erosion, wide-spread dust-storms and shrub mortality; extensive surveys and re-assessment of carrying capacity by government (10), and pastoralist responses (11)

7. South-west Queensland, 1964-1967: Soil erosion and woody weed infestation, leading to government-sponsored South-West Strategy, review of carrying capacities and property amalgamation (12)

1. New South Wales, 1898-1902: Soil erosion, the impact of woody weed infestation, rabbit plagues, substantial financial losses and hardship; led to Royal Commission of 1901 (6,7)

3. 'Gascoyne', Western Australia, 1935-1940: Substantial loss of perennial shrubs, soil erosion and animal losses documented in the Royal Commission of 1940 and subsequent inquiries (9)

2. North East District, South Australia, 1925-1929: Substantial loss of perennial vegetation and soil erosion (8) resulting in government legislation to regulate carrying capacity

4. New South Wales, 1941-1944: Substantial dust storms and animal losses graphically portrayed in artist Drysdale's paintings and newspaper reports (7), supporting need for government action

Fig. 2. Map of Australian rangelands, locating and briefly describing the degradation episodes analyzed in this article (episode 5 is omitted; see *Materials and Methods*). Shading indicates pastoral areas (sheep or cattle), forward hatching indicates episode regions with longer droughts, and back hatching indicates shorter droughts (diamonds indicate New South Wales had one of each).

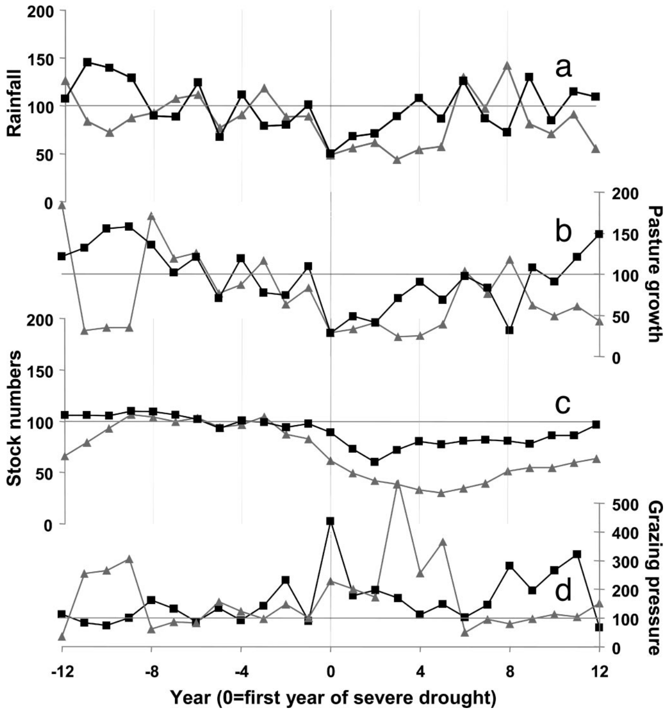


Fig. 3. Time course of various features of the drought episodes plotted annually relative to start year of drought for each episode. (*a*) Rainfall (% of mean annual rainfall in base period). (*b*) Simulated pasture growth (percentage of mean pasture growth in base period). (*c*) Reported stock numbers (percentage of mean number in base period). (*d*) Grazing pressure (the ratio between the stock numbers and pasture growth, reported as percentage, a value of 100% implies the same balance between stocking and pasture growth as in each episode's baseline period; greater values indicate more stock than pasture growth). Each graph shows the mean of episodes 2, 4, 7, and 8 with short drought periods (■) and episodes 1, 3, and 6 with long drought periods (▲). (Adapted from figures 2.9 and 2.10 in ref. 1.)

Fig. 3 shows how rainfall, simulated pasture growth, and reported domestic stock numbers varied through the episodes (as the means of two groups of episodes, one containing those with short drought events and the other with longer periods; SI Fig. 6 shows the richness of individual episodes). Consistent features of the seven episodes were reanalyzed from the original study in terms of the different arrows in Fig. 1.

Impacts of Environmental Factors on the State of the Environment (E → E). Environmental drivers affected the capacity of the environment to deliver the ecosystem services associated with the supply and reliability of pastoral production.

- Total grazing pressure (stock numbers and other unmanaged herbivores such as rabbits, kangaroos, and goats), and in some cases woody weed seedlings, increased in response to a period of moderate to above-average rainfall preceding each drought/degradation episode (Fig. 3 and SI Fig. 6). There were internal feedbacks; for example, the establishment of woody weeds reduced the production of pasture biomass and hence fuel for fires, thus increasing the likelihood of further woody plant establishment (27) (slow variables and evolving states; DDP P1 and P2; see Table 1).
- The sequence of drought years resulted in rapid decline in surface cover and revealed the extent of previous resource damage. Drought also further accelerated degradation processes, reducing forage production (thresholds and changing states; DDP P3).
- Partial recovery occurred during years of above-average rainfall, which might not occur until decades after the major degradation episode, potentially beyond useful management time frames. Recovery was affected both by the characteristics of the region and individual stocking strategies after the episode (costs of intervention above and below thresholds; DDP P3).

Impacts of Human Factors on the State of the Human Subsystem (H → H). Likewise, socioeconomic drivers affected the functioning of the human subsystem in ways that preconditioned its decision making about the environment.

- Favorable commodity prices in the years before the drought episode encouraged heavier stocking (misplaced focus on fast variables; DDP P2).
- Rapid decline in, or generally low, commodity prices early in most episodes (and in some cases financial reserves from prior good years to buy fodder) resulted in some pastoralists retaining far more stock than the forage could support in the hope of better sale prices or rain, or because of the fear of high costs of restocking (misplaced focus on fast variables, not addressing thresholds; DDP P2 and P3).
- Public support through fodder and transport subsidies and taxation policies (particularly in episode 8) encouraged pastoralists to retain stock on the land. The individual states have provided ad hoc drought assistance since 1866, and the federal government contributed under the National Disaster Relief arrangements from 1970 until a major policy review in 1990 (28) (interactions across institutional scales; DDP P4).

Impacts of Environmental Factors on the Human Subsystem (E → H). The state of the environment and the way in which it was delivering relevant ecosystem services had a series of consistent effects on the human subsystem at a variety of scales.

Short term. There was a general overexpectation by pastoralists, investors, and other institutions of how many stock the environment could safely support, usually driven by a decade of moderate environmental conditions before the degradation episode (Fig. 3*a*). This period was shorter than the time frame of bidecadal climatic variability and longer trends in the rangelands, but a significant proportion of the typical working lifetime of a pastoralist (20–40 years) and very long compared with political cycles (3 years) (mismatched temporal and institutional scales; DDP P4).

Medium term. Individual pastoralists learned from the environmental impacts they observed; Woodgreen Station in episode 6 (11), Moble Station in episode 7 (1), and Trafalgar Station in episode 8 (14) are three well documented examples. Anecdotal information, and behavior in subsequent droughts, indicates that this learning was not universal and could readily fade over time and as new pastoralists entered the industry. At a broader scale, the same was usually true in policy institutions (LEK development; DDP P5).

Long term. Whereas some of the regions recovered their capacity to carry stock after the drought episode, others appear to have experienced long-term damage or change in management risk attitudes that has enforced reduced stocking by properties in some regions to as little as 40% of the average before the episode (Fig. 3*c*). There has been documented social hardship and bankruptcy in these regions (see above) (thresholds for viability; DDP P3).

Impacts of Decision Making on the Environment (H → E). Human decision making at property and wider scales affected ecosystem services for pastoral production.

Short term. Intermittent dry seasons before the drought resulted in heavy grazing pressure and damage to the "desirable" perennial species, and ultimately to the grazing land resource over years. These preconditions triggered the rapid collapse in the ability of the land to carry animals at the onset of drought (slow variable interacting with thresholds; DDP P2 and P3).

Medium term. Extreme grazing pressure in the first years of drought (Fig. 3*d*, particularly the longer droughts) because of the decision to retain stock caused the further loss of perennial species, exacerbating the effects of drought in subsequent years. In the earlier episodes before trucking, it was hard to transport stock off the property; the remaining option of killing excess stock was rarely taken because there was always the possibility of rain in the near future. A crude indicator of grazing pressure (Fig. 3*d*) shows that it was at least two times higher than before the drought (exceeding thresholds; DDP P3).

Long term. Continued retention of stock through a long drought period (with animals often dying of starvation in large numbers) compounded damage to the resource and delayed (or prevented) recovery (slow variables and thresholds; DDP P2 and P3).

Discussion

The case study episodes thus have illustrated all of the linkages in Fig. 1 and highlighted all of the DDP principles (Table 1). Overly optimistic expectations were driven by relatively good seasons and prices, as individuals, industry, and institutions all neglected slow patterns of change in these. As a result, key thresholds were crossed in other slow variables, in both the human and environmental subsystems. Behind these proximate causes lay long-term climatic variability, economic pressures and institutional responses; in some cases at least, long-term impacts on environment and people resulted. The question thus arises, with this understanding, could we now do better?

Implications for Policy and Management. Future degradation episodes will only be avoided through better resource management, particularly of grazing and fire, and individual managers must ultimately implement this management. However, we have shown the human–environmental interactions that work against this outcome; economics drives short-term decisions that fail to be balanced by an understanding of long-term feedbacks because the long return times of some climatic cycles make it difficult for individual managers to learn about them. Although the importance of climatic oscillations like the El Niño–Southern Oscillation and the Interdecadal Pacific Oscillation have been well noted for drought (19, 21), the critical importance of the longer-term cycles for learning has not been highlighted. These cycles create a fundamental mismatch in temporal and institutional scales that inhibits the development of LEK.

Such failures must be resolved by institutions and industry agreements at a higher level than individual managers (DDP P3 and P4). It is apparent that, in another scale mismatch, historical institutions were unable to mobilize fast enough in earlier episodes to do other than record the results of a degradation event; such direct intervention is plainly too little, too late, and too insensitive to local conditions. Insightful government surveys, inquiries, or Royal Commissions were held during or after almost all of the drought sequences and documented the economic and environmental damage, but they were always too late to prevent damage in the contemporary episode. Although there is always a temptation to intervene with drought assistance during droughts (29), from the foregoing analysis this is clearly a response at an inappropriate scale in time and space. If there is to be such direct intervention it needs to be at a regional scale, and governments need to invest contextually over years rather than during an episode.

And indeed there has been a growing strategic institutional response, through science and policy, toward better information, tools, and incentives, which are at a more appropriate scale in space and time. First, there have been advances in science (often assisted by inputs from pastoralists' experiences); this is documented in relation to most episodes, most notably by Condon (7) after episode 4, Condon *et al.* (10) after episode 6, by Johnston (12) after episode 7, and in many studies after episode 8 (e.g., ref. 30). This improving understanding has led to various pastoralist-supported packages like Grazing Land Management (31) and the development of a national drought alert system (32). Second, national drought policy also continues to evolve, triggered by a major review in 1990. Although there remain many aspects of the system that are not ideal (29), there is also slow change, as instanced by the introduction of "farm management deposits" as a policy instrument in 1999 (these allow producers to put funds aside untaxed in good years to be redrawn when needed). Finally, a slowly maturing national monitoring system (33) is building the ability to detect whether this learning is reflected in improved landscape function at property to regional scales.

This response still has a considerable distance to travel, such that further development of the following components remains vital:

(*i*) Policies and administration that value the responsibility of managers to make day-to-day decisions on their properties (i.e., match the scale of decision making firmly with that of the environment) within the context of regional support for learning that provides them with tools to help improve those decisions (12, 30) and peer support to motivate their implementation.

(*ii*) Alert systems, at both local and regional scales, that use improved climatic understanding (19) and resource monitoring (33) to provide warnings of the potential for degradation episodes (32), taking account of the longer-term climatic cycles and trends that are beyond the likely experience of current managers. Forecasting rainfall and climate risk at 1- to 10-year time scales remains a high priority, to understand and warn of the impacts of quasi-decadal, bidecadal, and climate change signals.

In short, creating local knowledge through an alliance of industry, science, and institutional efforts at a regional and multigenerational scale is important for the future. Agreements between governments and industry on best practice must provide individual managers with access to institutionalized collective knowledge, extending this to new managers and exposing existing managers to new management options. The early 2000s have seen a further major drought in Australia, but it is too soon to be sure what progress has been made in changing management.

Implications for Land-Change Science. The DDP framework helped to structure the insights from this study for management and policy (Table 1), but this application also raised some insights for the science and the DDP. First, the scale at which LEK applies must be interpreted with caution; implicitly this is normally very local (34), for example, the shared mental models of a small community of neighboring pastoralists in this study. However, there is regional community understanding and policy-scale understanding about local management, which may be equally important in modulating the local links between human decision making and ecosystem services. In this study, LEK in the small pastoral community was being learned at a rate that was too slow relative to the turnover of pastoralists and their life experiences, because of the long periodicity in vital aspects of the climate system. It is not obvious how such learning could develop experientially in even a regional human community in the absence of an alliance between industry, government, and research at regional scales.

The importance of variability in the drivers is a second issue. Consider the following thought experiment. If climate had been less variable, would the coupled system have deteriorated because of the social drivers? We argue "much less likely," as the variability hampered learning; even despite this there is ample evidence of some learning in the system, but mostly at the wrong time and institutional scale. Equally, if the social drivers such as prices, technologies, and policies had been less variable, would the system have deteriorated because of drought? Again, we argue much less likely, as it was the human (discount factor-driven) response to variable social inputs that was a significant driver to pastoralists holding on to stock in these events; in situations with steadier contexts there is plenty of evidence of calculated planning. Thus we assert that the interactions between variability in both environment and human subsystems drove the damage observed in these episodes. This assertion may be the basis for a wider hypothesis that variability in both subsystems is a particular precursor to system failure, asserting the links between social and ecological resilience (35). In any case, it is apparent that there is value in monitoring the level of variability in key drivers as a slow variable in its own right. As land science is applied in a world that, under the influence of global environmental change, is becoming increasing variable in many ways, a focus on the variability rather than the mean of drivers is a vital requirement for future management and policy.

Last, while the DDP principles (4) have driven an analysis here that elucidated findings not highlighted in the original study (1), this analysis has in turn highlighted issues for the DDP. Notably, observing fundamental mismatches in temporal and institutional scales is particularly important in drylands, and the concept of LEK needs broadening to encompass larger social scales and policymaking.

Materials and Methods

This article draws on seven case studies of regional degradation events in different regions of Australia since settlement (see Fig. 2), which were selected from some 17 possible cases, mainly on the basis of better documentation (details in ref. 1). Here, we reanalyzed the key lessons from the case studies by using the DDP framework. P1 drove the framework of Fig. 1, and consistent features of the seven episodes, expressed in different ways in different regions, were identified by using DDP P2–P5, then categorized in terms of the different arrows in Fig. 1.

Some additional aspects of the methodology of McKeon *et al.* (1) are outlined in *SI Text*. For Fig. 3, the drought period for each episode (Fig. 2) was calculated by using the mean of regional rainfall for a standard 12-month period from April 1 to March 31 (identified by the initial calendar year, i.e., 1998 is April 98–March 99). The extended drought period was defined as having begun in the first year in which rainfall was <70% of this mean (year 0 in Fig. 3) and ended when rainfall more than mean occurred. The base period for the percentages presented was usually the 5 years before year 0, with some minor episode differences documented in ref. 1.

Note that McKeon *et al.* (1) examined eight episodes, but episode 5 (western New South Wales, 1964–1967, large increases in woody weeds during the 1950s caused by good rainfall and suppression of fire, the effects of which were only revealed in the 1960s drought) was qualitatively different to the others and omitted here; we have retained the original numbering of episodes to avoid confusion.

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1. McKeon G, Hall W, Henry B, Stone G, Watson I, eds (2004) *Pasture Degradation and Recovery in Australia's Rangelands: Learning from History* (Queensland Department of Natural Resources, Mines and Energy, Brisbane, Australia).
2. Turner BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, *et al.* (2003) *Proc Natl Acad Sci USA* 100:8074–8079.
3. Global Land Project (2005) *Global Land Project: Science Plan and Implementation Strategy* (International Geosphere-Biosphere Program Secretariat, Stockholm), International Geosphere-Biosphere Program Report 53/International Human Dimensions Program on Global Environmental Change Report 19.
4. Reynolds JF, Stafford Smith DM, Lambin EF, Turner BL, II, Mortimore M, Batterbury SPJ, Downing TE, Dowlatabadi H, Fernandez RJ, Herrick JE, *et al.* (2007) *Science* 316:847–851.
5. Stafford Smith DM, Reynolds JF (2002) in *Global Desertification: Do Humans Cause Deserts?*, eds Reynolds JF, Stafford Smith DM (Dahlem Univ Press, Berlin), pp 403–424.
6. Anonymous (1901) *Royal Commission to Inquire into the Condition of the Crown Tenants, Western Division of New South Wales* (Government Printer, Sydney, Australia).
7. Condon RW (2002) *Out of the West: Historical Perspectives on the Western Division of New South Wales* (Lower Murray Darling and Western Catchment Management Committees, Rangeland Management Action Plan, Wentworth, Australia).
8. Ratcliffe FN (1936) *Soil Drift in the Arid Pastoral Areas of South Australia* (Council for Scientific and Industrial Research, Government Printer, Canberra, Australia).
9. Jennings BG, Halleen DG, Wilcox DG, Ripley J (1979) *The Present and Future Pastoral Industry of Western Australia* (Lands Department, Western Australia Government Printer, Perth, Australia).
10. Condon RW, Newman JC, Cunningham GM (1969) *J Soil Conserv Service New South Wales* 25:47–92.
11. Purvis JR (1986) *Aust Rangeland J* 8:110–117.
12. Johnston PW, Tannock PR, Beale IF (1996) *Rangeland J* 18:259–269.
13. Gardener CJ, McIvor JG, Williams JC (1990) *Proc Ecol Soc Aust* 16:279–286.
14. Landsberg RG, Ash AJ, Shepherd RK, McKeon GM (1998) *Rangeland J* 20:104–118.
15. Noy-Meir I, Seligman NG (1979) in *Management of Semi-Arid Ecosystems*, ed Walker BH (Elsevier, Amsterdam), pp 113–160.
16. Geist HJ, Lambin EF (2004) *Bioscience* 53:817–829.
17. McKeon GM, Day KA, Howden SM, Mott JJ, Orr DW, Scattini WJ, Weston EJ (1990) *J Biogeogr* 17:355–372.
18. Nicholls N, Wong KK (1990) *J Clim* 3:163–170.
19. White WB, Gershunov A, Annis JL, McKeon G, Syktus J (2004) *Int J Climatol* 24:1911–1927.
20. Power S, Casey T, Folland C, Colman A, Mehta V (1999) *Clim Dyn* 15:319–324.
21. Folland CK, Renwick JA, Salinger MJ, Mullan AB (2002) *Geophys Res Lett* 10.1029/2001GL014201.
22. Burke EJ, Brown SJ, Christidis N (2006) *J Hydrometeorol* 7:1113–1125.
23. Webster MED (1973) in *The Environment, Economic, and Social Significance of Drought*, ed Lovett JV (Angus and Robertson, Sydney, Australia), pp 150–163.
24. Ker Conway J (1989) *The Road from Coorain* (Random House, Sydney, Australia).
25. McDonald R (1991) *Winning the Gascoyne* (Hesperian, Victoria Park, Australia).
26. Stehlik D (2003) in *Beyond Drought: People, Policy, and Perspectives*, eds Botterill LC, Fisher M (Commonwealth Scientific and Industrial Research Organization Publishing, Melbourne, Australia), pp 87–108.
27. Moore JL, Howden SM, McKeon GM, Carter JO, Scanlan JC (2001) *Environ Int* 27:147–153.
28. O'Meagher B, Stafford Smith M, White DH (1999) in *Drought, A Global Assessment*, ed Wilhite D (Routledge, London), pp 115–128.
29. Botterill L, Fisher M, eds (2003) *Beyond Drought in Australia: People, Policy, and Perspectives* (Commonwealth Scientific and Industrial Research Organization Publishing, Melbourne, Australia).
30. Scanlan JC, McKeon GM, Day KA, Mott JJ, Hinton AW (1994) *Rangeland J* 16:64–76.
31. Quirk M, O'Reagain P (2003) in *Science for Drought: Proceedings of the National Drought Forum*, eds Stone R, Partridge I (Queensland Department of Primary Industries, Brisbane, Australia), pp 101–105.
32. Carter JO, Hall WB, Brook KD, McKeon GM, Day KA, Paull CJ (2000) in *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems: The Australian Experience*, eds Hammer G, Nicholls N, Mitchell C (Kluwer, Dordrecht, The Netherlands), pp 329–349.
33. Australian Collaborative Rangeland Information System (2001) *Rangelands—Tracking Changes* (National Land and Water Resource Audit, Australian Government, Canberra, Australia).
34. Robbins PF, Abel N, Jiang H, Mortimore M, Mulligan M, Orkin GS, Stafford Smith DM, Turner BL, II (2002) in *Global Desertification: Do Humans Cause Deserts?*, eds Reynolds JF, Stafford Smith DM (Dahlem Univ Press, Berlin), pp 325–355.
35. Adger WN (2000) *Progr Hum Geogr* 24:347–364.