Review

Agricultural modifications of hydrological flows create ecological surprises

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Agricultural expansion and intensification have altered the quantity and quality of global water flows. Research suggests that these changes have increased the risk of catastrophic ecosystem regime shifts. We identify and review evidence for agriculture-related regime shifts in three parts of the hydrological cycle: interactions between agriculture and aquatic systems, agriculture and soil, and agriculture and the atmosphere. We describe the processes that shape these regime shifts and the scales at which they operate. As global demands for agriculture and water continue to grow, it is increasingly urgent for ecologists to develop new ways of anticipating, analyzing and managing nonlinear changes across scales in human-dominated landscapes.

Humans have modified the water cycle through agriculture

Human transformation of global water flows has dramatically impacted ecosystems and the services they generate. Through water withdrawals, land use and land cover changes, agriculture, which covers almost 40% of the terrestrial surface [1], is arguably the major way in which humans change water quantity and quality (Box 1). Water for irrigation accounts for 66% of societal water withdrawals, reducing water availability for downstream ecosystems [2]. Irrigation and deforestation for agriculture have redistributed global evapotranspiration, altering the regional climate [3]. Nutrient runoff from agricultural fertilizer use has decreased water quality in aquatic ecosystems around the world [4,5]. These changes have driven rapid declines in nonagricultural ecosystem services, such as fisheries, flood regulation and downstream recreational opportunities [6]. Despite these impacts, increases in agricultural production have reduced malnutrition and hunger, and agriculture has been an engine of economic growth in many countries. The complex trade-offs between increased agricultural production and declines in other ecosystem services as caused by agricultural changes to the hydrological cycle have been reviewed by the Millennium Ecosystem Assessment (MA) [6] and the Comprehensive Assessment of Water Management in Agriculture (CA) [7]. Their reviews of research needs revealed that although knowledge of these trade-offs has increased, we lack an integrated understanding of how agricultural modifications of the hydrological cycle regulate the prevalence and severity of surprising nonlinear change in ecosystems [7,8].

Some of the most catastrophic changes in ecosystem services are a result of nonlinear, abrupt shifts between different ecosystem regimes (Box 2). Regime shifts are frequently surprising and difficult to reverse, presenting a substantial challenge to ecosystem management and development goals [9–11]. A rapidly growing body of evidence suggests that agricultural modification of the quality and quantity of hydrological flows can increase the risk of ecological regime shifts [12–17].

An improved, synthetic understanding of how such regime shifts are produced is particularly urgent now because of growing demand for water, agricultural products such as food and biofuels, and other ecosystem services such as carbon sequestration, climate moderation, erosion control and opportunities for recreation. Climate change that is expected to generate unprecedented alterations in precipitation, soil moisture and runoff will make negotiating the complex hydrology-related ecological trade-offs of agriculture even more challenging. In this paper, we review how agricultural modification of the hydrological cycle can produce regime shifts. We emphasize the key agricultural and hydrological processes involved in regime shifts and the spatial and temporal scales at which these processes operate. We conclude by discussing management challenges for building resilience against undesired regime shifts, and highlight important research questions that need to be addressed to reduce the risk of future agriculture–water surprises.

Three parts of the hydrological cycle where agriculture can trigger regime shifts

The hydrological cycle can be seen as the 'bloodstream of the biosphere' [18], because runoff, groundwater and evapotranspiration move materials among different ecosystems and alter energy balances in landscapes. This paper examines how agricultural changes across the whole hydrological cycle can produce regime shifts. We classify

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Box 1. Historical and future demand of land and water for agriculture

Agricultural production, and its related hydrological changes, has greatly increased during the 20th century. Figure I shows (i) agricultural land use, including croplands and rangelands over the past 300 years [2], (ii) the amount of societal water withdrawal for irrigation since 1900 [2] and (iii) the increase in agricultural fertilizer use since 1960 [64].

These changes are expected to continue in the 21st century. Population growth, the production of biofuels and increased meat consumption are driving increased agricultural demands. The Millennium Ecosystem Assessment scenarios estimated that future agricultural expansion would convert between 10% and 20% of existing forest and grassland to cropland, with this conversion expected to be concentrated in low-income countries and in drylands [6]. The nations of the world have pledged in the UN Millennium Development Goals to halve the proportion of people who suffer from malnutrition by 2015, and to eradicate hunger by 2030. Meeting these goals in targeted countries will require a 50% increase of food production by 2015 and at least a doubling at 2050, with water consumption (in terms of evapotranspiration) increasing from 4500 km^3/yr to 7300 km^3/yr in 2050 [65]. The Comprehensive Assessment of Water Management in Agriculture (CA) developed scenarios for 2050, suggesting that depending on investment strategies, trade and improvement of technology, water demands for agriculture will rise 30%–54%, while agricultural area will expand between 9% and 38% [7].

The CA stressed the importance of improving water productivity, which is most often measured as m^3 of evapotranspiration used per ton of grains. Water productivity can be increased by reducing unproductive losses of water, such as soil evaporation, while increasing productive water flows (transpiration). The highest gains in water productivity can come from improvements in low-yielding agriculture when supplemental irrigation is combined with improved tillage and nutrient management [66]. The CA scenarios showed that increased water productivity has the potential to reduce future water needs by more than 50%, compared to future water needs without any improvements in water productivity [7]. However, the potential trade-offs between locally improved water productivity and potential downstream water quality decline from increased use of fertilizers and pesticides due to increased water productivity are scarcely addressed in the literature and illustrate the need to enhance our capacity to analyze multiple trade-offs.

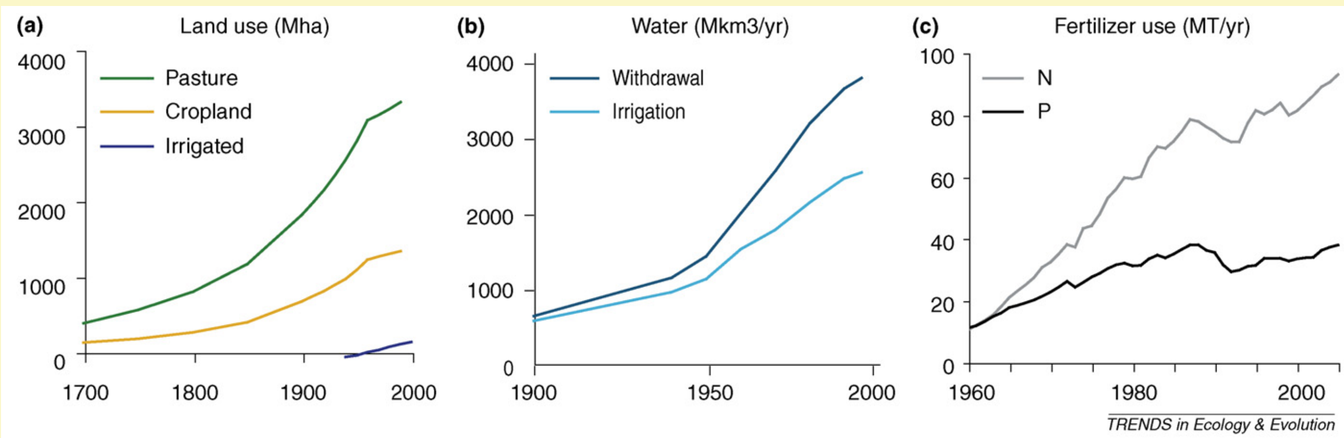

Figure I. Agriculture's extent and modification of the quantity and quality of hydrological flows have increased over the past centuries.

agriculture–water regime shifts into three categories depending on where they occur in relation to the hydrological cycle (Figure 1). These categories are:

(i) agriculture and aquatic systems, including changes in runoff quality and quantity that lead to regime shifts in downstream aquatic systems (Figure 1a);
(ii) agriculture and soil, in which changes in infiltration and soil moisture result in terrestrial regime shifts (Figure 1b); and
(iii) agriculture and the atmosphere, in which changes in evapotranspiration result in regime shifts in the climatic system itself or in terrestrial ecosystems as a consequence of climatic changes (Figure 1c).

Agriculture and aquatic systems

Agriculturally driven change in water flows, nutrient levels and sediment loads can produce regime shifts in downstream aquatic systems in at least three different ways (Table 1). Nutrients such as phosphorus and nitrogen in fertilizers can move downhill in runoff, leading to freshwater and estuarine eutrophication [19] that might be reversible only after massive reductions of nutrients for decades or longer [20]. Decomposition of large amounts of organic matter produced by excess nutrients in estuaries can lead to areas of depleted oxygen called hypoxic zones [21]. These can have alternative regimes due to recycling of nitrogen stored in sediments during previous years. This feedback can, however, be weakened owing to temperature, water movement and the availability of other nutrients [22]. Freshwater and estuarine eutrophication regime shifts caused by phosphorus can be a result of accumulation of phosphorus in aquatic sediments as well as in agricultural soils. Accumulated phosphorus in sediments can be released to the water column under the low-oxygen conditions common to eutrophication, setting in motion a positive feedback cycle in which low oxygen caused by high nutrient levels leads to additional phosphorus released to the water column [19,23]. Furthermore, phosphorus can also be accumulated in agricultural soils when not all of the applied phosphorus is taken up by plants [5]. Because soil phosphorus concentrations change slowly, this accumulation might set the stage for decades, if not centuries, of impaired water quality, even after phosphorus input to terrestrial systems has stopped [20].

Another aquatic system regime shift is changes in river channel position [24], common in river deltas when agricultural land use affects sediment loading and channel veg-

Box 2. Ecosystem regime shifts

Ecological dynamics are defined by both internal dynamics (such as vegetation growth) and external forces (such as precipitation and droughts). Regime shifts occur when external forces or gradual internal changes alter a system so that its organization shifts from being organized around one set of mutually reinforcing processes (e.g. vegetation enhancing precipitation) to another (e.g. less vegetation, no effect on precipitation) [10,11,15]. Resilience is related to the concept of regime shifts and is defined as the capacity to deal with change and disturbances while retaining essentially the same functions and processes [11].

Figure I illustrates the differences between gradual ecological change and three different types of regime shifts using precipitation–vegetation interactions as an example [15,17,42]. The feedbacks that maintain a system in a given regime are represented as the shape of stability landscapes (Figure I, upper panel), with the configuration of the system represented by a ball. Multiple valleys in the landscape represent the potential of having alternative regimes. External shocks (such as a drought or an intense rainfall event) can change the system configuration, moving the ball across the landscape. However, the stability landscape itself can also change as the forces defining the feedback processes in the system change, for example, through vegetation clearing or changes in soil moisture holding capacity. Changes in internal variables that alter the feedback processes that define a regime are often relatively slower than other system dynamics that people monitor, such as yield levels. They are thus often referred to as 'slow variables.' If a valley in the stability landscape completely vanishes, or an external shock pushes the system from one valley to another, the system undergoes a regime shift. Equilibria diagrams (Figure I, lower panel) summarize how the dynamics of an ecosystem change as ecological drivers change. The colored dotted lines show where each stability landscape is located on each equilibria diagram.

Gradual change (Figure Ia) occurs when precipitation increases from drier to wetter conditions in a landscape that contains species whose growth responses to increasing vegetation are diverse and relatively evenly distributed so that vegetation cover gradually increases with precipitation. Threshold change (Figure Ib) occurs when vegetation cover rapidly increases at a specific amount of precipitation. Changes in external drivers can in systems with thresholds push a system from dense to spare vegetation cover. Hysteresis (Figure Ic) can occur if there is strong moisture recycling from vegetation that stimulates precipitation; this implies that the precipitation thresholds at which vegetation will quickly increase (recovery) are higher than precipitation levels at which vegetation will collapse. Irreversible change (Figure Id) is a stronger form of hysteresis, where vegetation is unable to recover to its pre-collapse levels, even if rainfall increases substantially. This type of dynamic can occur when the ability of vegetation to recover is lost from the system during a collapse.

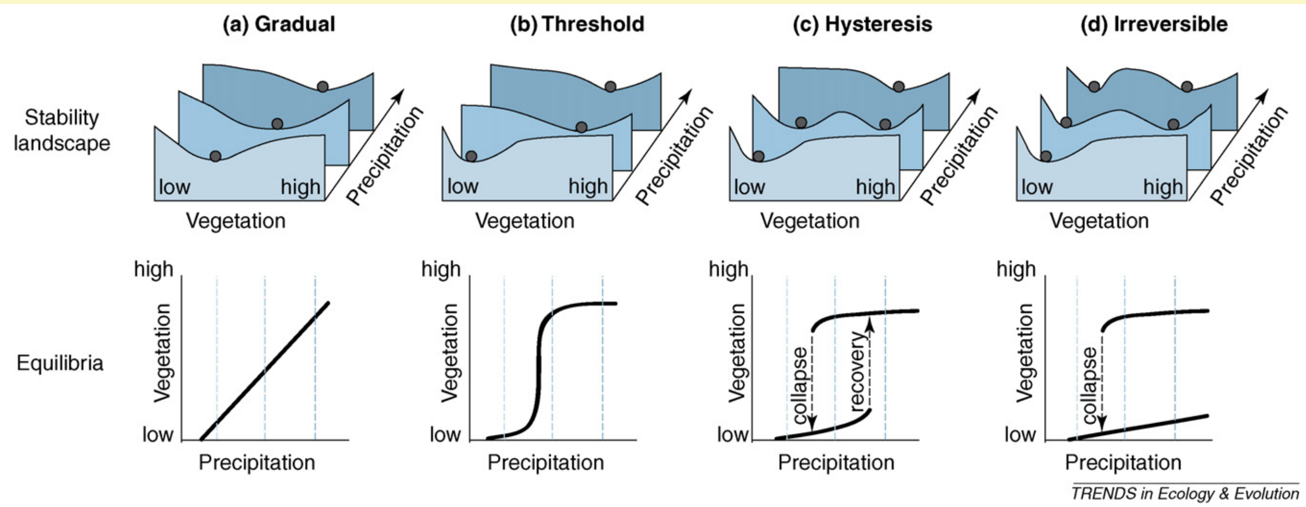

Figure I. The differences between gradual ecological change **(a)** and three different types of regime shifts **(b–d)** using precipitation–vegetation interactions as an example.

etation [25]. Rivers overloaded with sediment from eroded agricultural soils can experience channel incision [26], in which increased scouring causes loss of channel vegetation, which can, in turn, lead to the abrupt formation of highly eroded channels [27]. In other cases, sediment load blocks the path of the river, causing the river to suddenly form a new course. It can take centuries or longer for the river to return to its original course, if it ever does so [24].

Agriculture and soil systems

Interactions between vegetation and soil water, through effects on infiltration, soil water holding capacity and root water uptake cause at least three types of regime shifts leading to land degradation and loss of productivity (Table 1). The first is related to vegetation patchiness that can impede the flow of surface water, creating spatially concentrated patterns of infiltration that locally increase nutrient and water accumulation, which in turn sustains vegetation growth and landscape patchiness [14,28,29]. Grazing can shift systems to a less productive regime by reducing vegetation cover, setting in motion a feedback that decreases nutrient and water accumulation [29,30]. Similarly, in arid to semiarid savanna systems, regime shifts between grass and shrub domination can occur if the existing competition between grasses and shrubs for water in the root zone is destabilized. This competition can be altered by grazing that removes less drought-sensitive species, by differing patterns and intensity of fire and by changes in drought occurrence [31].

A second type of regime shift occurs when a rise in the water table triggers salinization. Water table rise occurs when more water infiltrates the soil, owing to irrigation or increases in precipitation, or when less water is removed due to reductions in evapotranspiration when deep-rooted trees are replaced with annual crops or grasses. The resulting water table rise can mobilize salts in the soil. The process speeds up when a water table has risen to within ~2 m of the surface, because capillary action

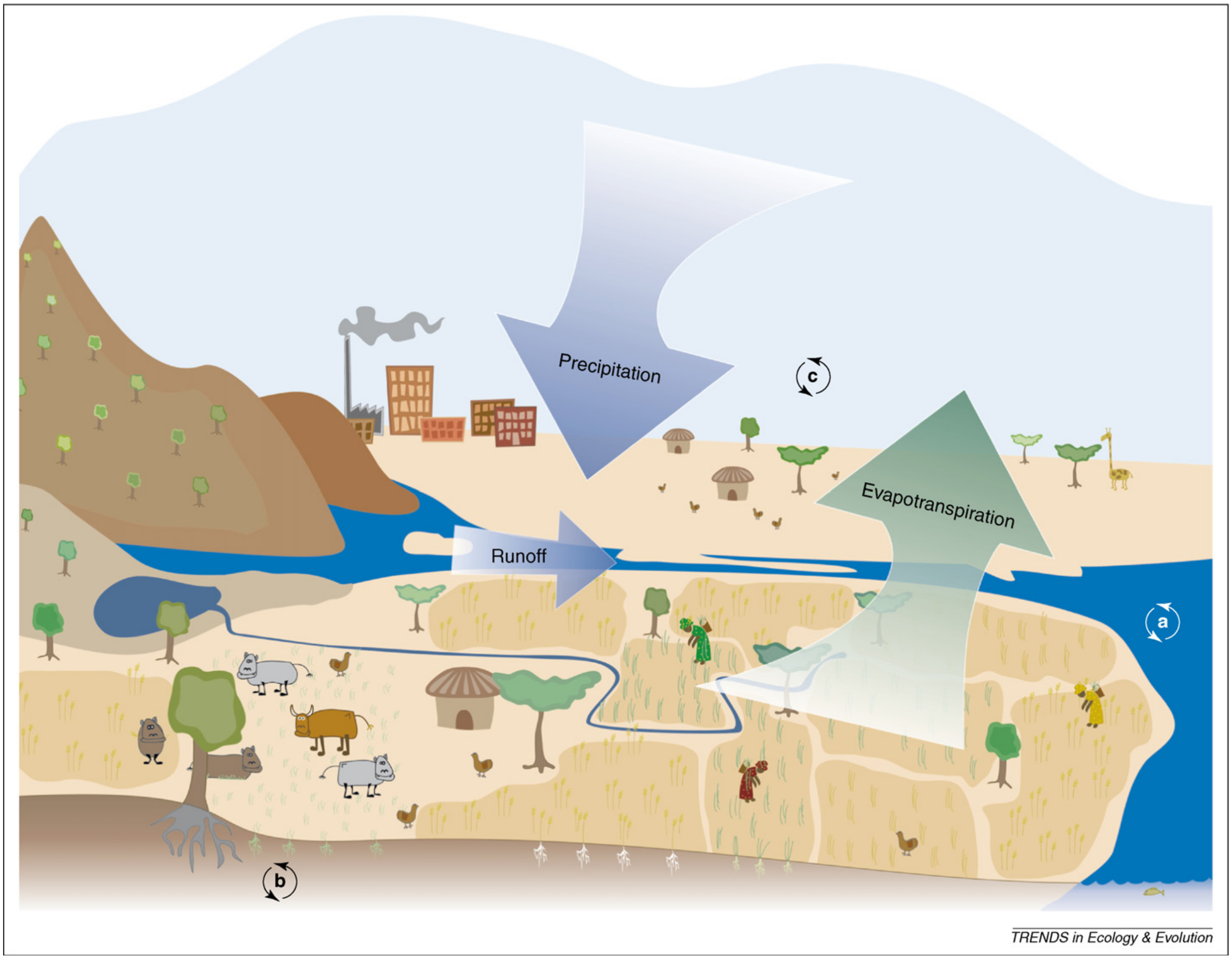

Figure 1. Locations of regime shifts in the hydrological cycle. Conceptual diagram showing three main flows in the hydrological cycle (precipitation, runoff and evapotranspiration) and where in the hydrological cycle three potential regime shifts produced by couplings between agriculture and water flows can occur: **(a)** agriculture and aquatic systems, **(b)** agriculture and soil and **(c)** agriculture and atmosphere regime shifts.

through fine pores can then move water to the surface, carrying salt with it. Salts present in the soil become concentrated in the plant rooting zone making the soil inhospitable to vegetation, resulting in regime shifts difficult to reverse or irreversible [32,33]. Finally, it has been suggested that reductions in the length of fallow periods in semiarid croplands can result in rapid yield declines once fallow periods fall below a critical threshold [34]. Fallow periods allow for restoration of soil organic matter and nutrient levels. Reduced fallows can lead to changes in soil structure including compaction and crusting that renders soils more drought sensitive by decreasing soil moisture holding capacity [35]. Soil water availability is crucial to sustain yields and productivity, because highly variable precipitation in drylands produces recurrent dry spells and droughts [36]. The evidence for this type of regime shift is relatively weak. However, although soil structure regime shifts might be biophysically quite easy to reverse, decreasing incentives to invest in degraded soils implies that there can be stronger economic than biophysical thresholds for the reversibility of these shifts [37].

Agriculture and the atmosphere

Land cover conversion for agriculture impacts precipitation and can produce at least four different regime shifts. Many regional to global studies of vegetation–climate interactions have shown that changes in vegetation cover can alter precipitation [38,39]. Some of these studies have assessed whether these interactions can produce regime shifts [40]. Theory suggests that regime shifts can occur if two conditions are fulfilled [17,41]. First, the vegetation cover has to respond nonlinearly to changes in precipitation (Box 2, Figure Ib–d) and second, vegetation has to have a sufficiently strong effect on precipitation that it can, in turn, alter the amount of vegetation cover (Box 2). The strongest evidence for land–atmosphere regime shifts comes from studies of the shifts between wet savanna systems and dry savanna systems in the Sahara and the Sahel. Paleoecological records show that vegetation collapsed relatively abruptly ~5500 years ago, demonstrating that regime shifts can occur in this region [42]. Modern empirical evidence has shown that vegetation in the Sahel responds nonlinearly to changes in precipi-

Table 1. Regime shifts from agriculture changes in water quality and quantity, showing alternative regimes, consequences of the regime shift, key internal variables, agricultural drivers of change, other drivers and assessment of the evidence for the reality of each shift

Regime shift	Regime A	Regime B	Impacts of shift from A to B	Internal slow variable	Agricultural driver	Other drivers	Evidence	Refs
Freshwater eutrophication	Eutrophic	Non-eutrophic	Reduced access to recreation, drinking water, risk of fish loss	Sediment and watershed soil phosphorus	Nutrient and soil management	Flooding, landslides	Strong	[19,20,23]
Coastal hypoxic zones	Hypoxic	Not hypoxic	Fishery decline, loss of marine biodiversity, toxic algae	Aquatic biodiversity	Nutrient and soil management	Flooding	Strong	[4,21,22]
River channel position	Old channel	New channel	Damage to trade and infrastructure	River channel shape	Erosion, river channelization	Extreme floods, climate	Strong	[24,25,27]
Vegetation patchiness	Spatial pattern	No spatial pattern	Productivity declines, erosion	Vegetation pattern	Grazing, land clearing	Fires, droughts	Medium	[14,28,29]
Salinization	High productivity	Low productivity	Yield declines, salt damage to infrastructure and ecosystems, contamination of drinking water	Water table salt accumulation	Reduced evapotranspiration, irrigation	Wetter climate	Strong	[32,33]
Soil structure	High productivity	Low productivity	Yield decline, reduced drought tolerance	Soil organic matter	Biomass removal, fallow frequency	Droughts, dry spells	Weak	[35–37]
Wet savanna-dry savanna	Wet savanna	Dry savanna or desert	Loss of productivity, yield declines, droughts/dry spells	Moisture recycling, energy balance	Reduced net primary production and evapotranspiration	Droughts, fires	Medium	[42–44]
Monsoon circulation	Monsoon	Weak or no monsoon	Risk for crop failures, changed climate variability	Energy balance, advective moisture flows	Land cover change, irrigation	Change in sea surface temperature	Weak	[42,50]
Forest-savanna	Forest	Savanna	Loss of biodiversity, changed suitability for agricultural production	Moisture recycling, energy balance	Reduced net primary production	Fires	Weak	[31,41, 45,46]
Cloud forest	Cloud forest	Woodland	Loss of productivity, reduced runoff, biodiversity loss	Leaf area	Land clearing	Fog frequency	Medium	[51,52,60]

tation, and recent modeling studies have suggested that these changes in vegetation can produce precipitation feedbacks to vegetation that could enable regime shifts [17,42–44].

Transitions of forests to savannas has been suggested as a regime shift in the Amazon region, although the evidence for this type of shift is weaker [45]. The possibility of alternative regimes in the Amazon has been suggested by several studies of vegetation–climate interactions, including both models and statistical analysis of observations [41,45,46]. Amazonian vegetation has in other studies shown a surprising resilience to drought [47], but these studies did not include the impact of agricultural fires, which can reduce the resilience of forest to drought [48]. Another regime shift with even less evidence is shifts in monsoon behavior as a consequence of land cover change. It has been suggested that monsoon systems can exhibit regime shifts where the strength of the monsoon can influence vegetation, and where the strength of the monsoon also depends upon that vegetation [40,49]. Monsoon collapse has been suggested to be a driving force in the Sahel regime shift [40,42] and vegetation regime shifts in Australia [50].

At a smaller scale, agriculture–atmosphere regime shifts also can occur in cloud or fog forests, where moisture that vegetation intercepts from fog allows the vegetation to persist despite low precipitation. Without large enough leaf area to intercept fog, there is insufficient moisture capture to establish vegetation. Clearing of vegetation can thus result in a regime shift to a savanna or shrubland [51,52].

There is large variation in the spatial scales and reversibility of regime shifts

The regime shifts we have identified as related to agricultural changes to water flows (Table 1) operate at a wide range of spatial scales and are reversible at different temporal scales (Figure 2). Agriculture–aquatic system regime shifts occur at the watershed to river basin scales but vary from years to millennia in their reversibility. For example, freshwater eutrophication is often irreversible, or only reversible after massive reductions of phosphorus inputs for decades or longer, owing to internal cycling of phosphorus within the lake system and accumulation of phosphorus in watershed soils [20]. Agriculture–soil regime shifts tend to operate at field to landscape scale with varying degrees of reversibility. Although soil structure regime shifts occur at small spatial scales, their impact can cascade across the landscape, as exemplified by the development of the Dust Bowl in the 1930s in the US. The Dust Bowl started at the scale of individual fields and expanded nonlinearly to impact the agricultural

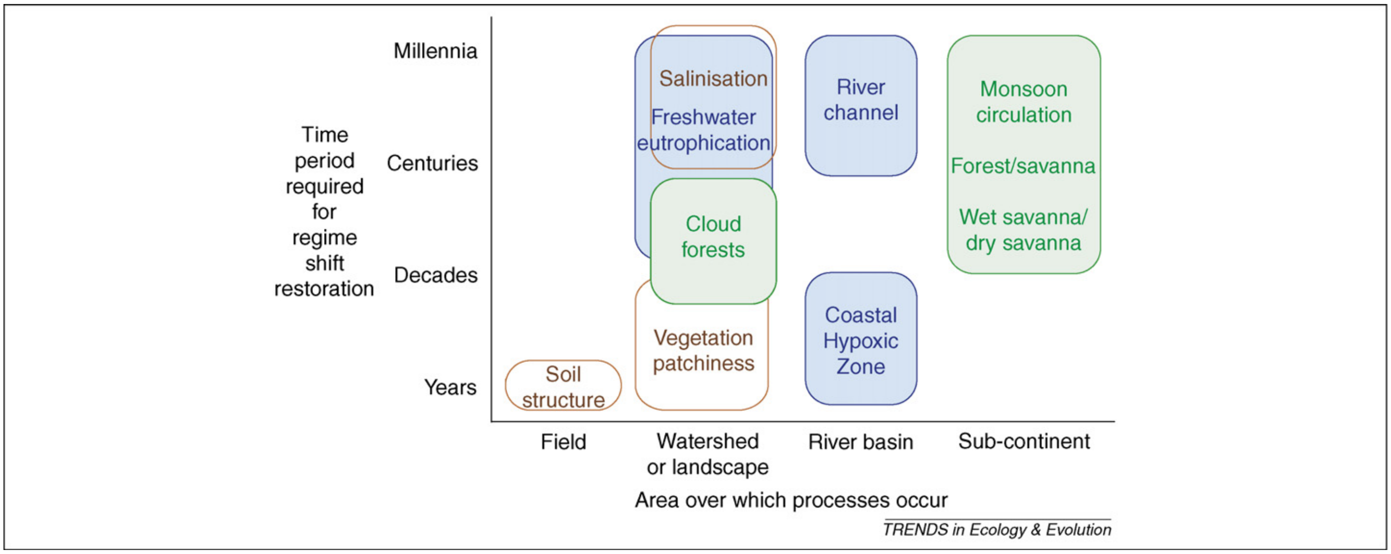

Figure 2. Estimates of the spatial and temporal scales at which regime shifts operate. Blue indicates agriculture and aquatic systems, white indicates agriculture and soil, and green indicates agriculture and atmosphere regime shifts.

regions of the US [12]. Broad-scale weather patterns caused individual fields to become highly connected, creating massive dust storms that nonlinearly aggravated the situation [12].

Finally, agriculture–atmosphere regime shifts tend to operate at relatively large spatial and temporal scales, although uncertainty remains about the important scales of land–atmosphere feedbacks. For example, although evapotranspiration from the forests is the main source of water for precipitation in the Amazon, patchy regional deforestation that increases landscape heterogeneity can contribute to an increase in rainfall through the establishment of anomalous convective circulations, whereas large-scale deforestation would substantially decrease precipitation even in very distant places [53].

Agriculture interacts with other drives to produce water-related regime shifts

Regime shifts are triggered by the interaction of changes internally in a system and changes in external drivers (Box 2). In Table 1, we identify critical internal 'slow variables' that strongly influence the vulnerability of an ecosystem to regime shifts. Managing these slow variables to maintain resilience can thus be an important management strategy. We also identify the external drivers that can produce regime shifts, separating these into agricultural and non-agricultural drivers. In many cases, agricultural drivers interact with other external drivers, such as climate change, in triggering regime shifts. For example, reduced soil organic matter, a critical slow variable, can lead to decreased water holding capacity. Less water in the soil reduces capacity to cope with a high frequency of dry spells [35,36]. In the Mississippi Valley, increasing precipitation in the late fall and spring influences nitrogen runoff, which expands the size of the hypoxic zone in the Gulf of Mexico [22]. It has been suggested that the recent drought in the Murray-Darling Basin in Australia has reduced the rate of dryland salinization expansion because the drought has kept water tables low. Consequently, the return of wetter conditions could have disastrous consequences [33]. As these examples show, hydrological consequences of climate change might move ecosystems closer to some critical thresholds and away from others, thereby influencing their vulnerability to other agriculturally induced changes in hydrology.

Enhancing resilience of agricultural landscapes

Hydrological alterations due to growing agricultural demands (Box 1) are likely to increase the risk of surprising regime shifts unless management practices are changed. The expected alterations can be reduced by improving the productivity of water in agriculture (Box 1), but enhancing resilience to the regime shifts discussed here requires active management of ecosystem processes across agricultural landscapes. Avoiding the discussed regime shifts is thus not only a question of improving management of water or agriculture. Here we identify some general strategies of enhancing ecosystem resilience to water–agriculture regime shifts by focusing on ecology as a vital part of resilience building.

From crop optimization to functional diversity

The management of agricultural systems has tended to focus on maximization of yield, emphasizing the production of a single ecosystem service at the expense of other ecosystem services. Changing the focus of agricultural management to how to reliably and profitably produce food while also producing other ecosystem services was a key recommendation of the MA and CA [1,7,8]. This change in focus could help increase resilience to regime shifts by maintaining or enhancing functional and response diversity in agricultural landscapes [54]. Functional diversity is the species diversity that maintains a specific ecosystem function, whereas response diversity is the diversity of responses that different species have to variations, and they are particularly important for reorganization after disturbance [10,54]. One of the major ways in which regime shifts can become irreversible is if the ecological processes that maintain a regime vanish from the landscape. For example, fragmentation of the Australian

Box 3. Locating regime shifts in the Earth system

Agricultural and other land use activities have often been seen as a local management issue despite pervasive global impacts [1]. Most evidence for regime shifts comes from local case studies. There are few analyses of the larger-scale distribution of regime shifts and their potential implications on the Earth system, despite a need for improved capacity of analyzing regime shifts at the global scale. Hotspots of expected aquatic regime shifts, driven by increased fertilizer use, can be found around the globe in areas that combine intensive agriculture, high fertilizer use, high animal density, naturally nutrient-rich soils, high rainfall and high rates of soil erosion [21]. All the soil regime shifts occur in drylands. Drylands are also the areas with the largest water challenges for reaching the United Nations Millennium Development Goals on hunger and malnutrition [65], and have been identified as particularly vulnerable to a complex set of interacting problems including land degradation, persistent poverty, population growth and remoteness of decision making and infrastructure [6,67]. Hotspots related to soil regime shifts are thus likely to occur in drylands with large populations (or population growth), high poverty and large needs-increased food production. There have been various attempts to identify regions vulnerable to changes in land–atmosphere interactions [39,68,69]. One of the factors that appear to control vulnerability to agriculture–atmosphere regime shifts is the extent to which local evapotranspiration versus evapotranspiration from oceans influences precipitation at different scales. In Figure I, we show where areas of deforestation and irrigation already have modified evapotranspiration [3], and where these areas coincide with regions where soil moisture has been suggested to have a substantial impact on rainfall [69]. Changes in evapotranspiration owing to deforestation for agriculture or irrigation are shown in yellow to red for decrease, blue for increase and green for no change (where gray is nonagricultural lands) [3]. The regions where precipitation (summer rainfall) is suggested to be strongly affected by soil moisture anomalies was identified in an assessment of land–atmosphere coupling strength across 12 global land–atmosphere climate models [69]. The circles in the figure indicate where these regions coincide with areas of changes in evapotranspiration. These overlaps suggest regions in the Earth system that could be the focus for more in-depth analysis.

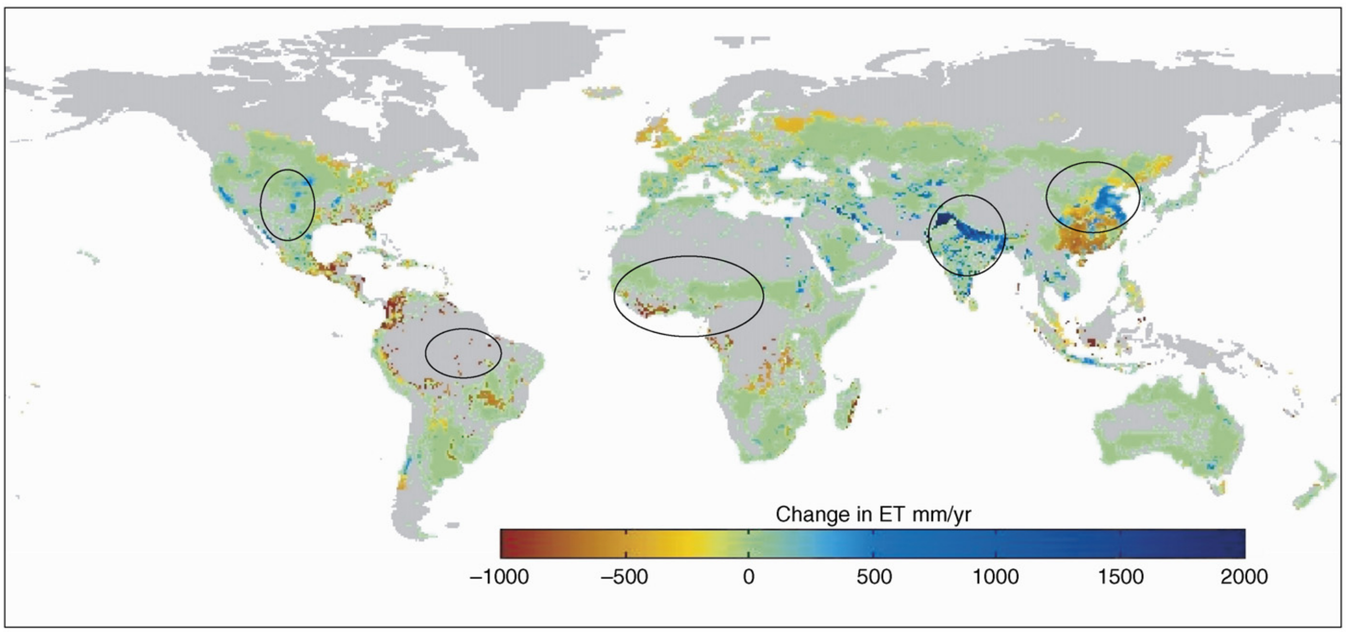

Figure I. Regions where deforestation and irrigation already have modified evapotranspiration, and where they coincide with areas where soil moisture has been suggested to have a substantial impact on rainfall.

landscape altered hydrology producing dryland salinity, but fragmentation also reduced plant reproduction and propagule dispersal, reducing the ability of the systems to recover from salinization when hydrology is restored [32]. This illustrates the importance of sustained habitats for species that can connect the landscape (so-called mobile links) by providing ecological functions such as seed dispersal [55].

From homogeneous fields to heterogeneous landscapes

We showed earlier that changes in vegetation patterns from overgrazing can increase the risk for regime shifts in arid to semiarid systems [30], whereas stimulating water infiltration at critical spots can help restore the system [29]. Spatial heterogeneity can also be an important factor in other types of agricultural landscapes, and for building resilience to other types of water-related regime shifts. Spatial heterogeneity can, for example, play a vital role in identifying and managing particularly vulnerable regions as well as critical areas that have a disproportionately high influence on the risk for regime shifts in the larger region. Because of variation in ecological processes across a landscape, some locations will be more vulnerable to regime shifts than others. By identifying locations where the forces that maintain an existing regime are weak, managers can identify where regime shifts are likely to occur [56]. For example, some savanna systems can exhibit regime shifts between forest and savanna, whereas other sites that are wetter or drier only have one possible regime [31]. In Box 3, we discuss vulnerable areas at a global scale. Identifying critical areas can allow managers to focus their rehabilitation or monitoring efforts where they are likely to have the greatest effect. For example, relatively small areas in watersheds that combine high soil phosphorus concentrations and high runoff potential are disproportionately responsible for the majority of phosphorus runoff into freshwater lakes [57]. Water quality can thus be substantially improved by managing these 'critical source areas' rather than managing an entire catchment [58].

From stability to dynamics

Ecosystems change as a result of internal and external processes, but management and policy often assume them to be relatively stable, neglecting to plan or manage for disturbance and reorganization [11]. Management that adapts to variation in external drivers can increase resilience. For example, grazing management that accounts for variability of rainfall rather than considering only average conditions can increase rangeland productivity [59]. Alternatively, extreme events can be used to engineer a regime shift. For example, rainy periods associated with El Nino can be used in combination with grazing reduction to restore degraded ecosystems, whereas grazing reduction alone is insufficient to achieve this goal [60].

Changes in internal variables that alter the processes that define a regime (Box 2) are often relatively slower than other monitored system dynamics, such as yield levels. Change in these slow variables might go unnoticed over long time periods, because researchers tend not to measure them until the system shifts to a new regime. For example, despite some early indications of how clearing of woody vegetation could increase risks of salinization in Australia already in the 19th century, Australians were in general unaware of this phenomenon until salinization started to become widespread [33]. Identifying and monitoring slowly changing key ecological processes, such as the water table rise in Australia, can be used to predict the likelihood of a regime shift. The ability to manage systems to avoid regime shifts in a world of high variability would be improved if we could predict how close an ecosystem is to critical thresholds. The creation of methods that provide early warning of regime shifts is an important scientific challenge, and research suggests that changes in pattern formation and rising variance could be used to detect when and where systems are becoming more likely to experience regime shifts [30,61].

From disciplinary divides to hydrological integration

The identified regime shifts (Table 1) created by agricultural modification of the hydrological cycle present a challenge to ecosystem governance, because water often transmits the consequences of change to locations which are spatially and temporally separated from the place where the change occurred (Figure 2). Coping with these disconnects can be improved by governance systems that connect local agricultural management practices to the scales that key ecological processes operate [62]. Because regime shifts are often a surprising outcome of slow change, governance that is able to learn how to effectively anticipate, avoid and respond to abrupt ecological change will be better prepared for future surprises [62]. Achieving this goal requires better biophysical understanding of the key feedback processes that connect regime shifts at different scales [17,43,44]. Discovering regime shifts in empirical data also requires the development and use of statistical methods specifically designed to detect evidence of abrupt shifts in long-term data [63]. Ecologists need to be involved in making sure these goals are met. Although this is a complex and difficult endeavor, one way to start is to identify key regions based on where we expect regime shifts to be more likely or more common, and focus research and management efforts on these (Box 3).

Conclusions and research challenges

There is strong evidence that agricultural modification of water flows can produce a variety of ecological regime shifts that operate across a range of spatial and temporal scales. In a world of growing demands for water, agricultural products and other ecosystem services, there will inevitably be ecological surprises. Preparing for these surprises is essential to maintain ecosystem services of importance for human well-being. Preparation requires understanding the forces that drive these regime shifts, as well as better methods designed specifically to anticipate and analyze them. Identifying ways of building resilience to these shifts illustrates the need to manage agriculture as an embedded part of larger landscapes, with special attention to the internal and external dynamics that drive change in inter-linked agricultural, hydrological and ecological processes. Achieving this will require increased scientific and policy collaborations among ecologists, agronomists, hydrologists and global change researchers.

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References

1 Foley, J.A. *et al.* (2005) Global consequences of land use. *Science* 309, 570–574
2 Scanlon, B.R. *et al.* (2007) Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. *Water Resour. Res.* 43, DOI: 10.1029/2006WR005486 (http://www.agu.org/journals/wr)
3 Gordon, L.J. *et al.* (2005) Human modification of global water vapor flows from the land surface. *Proc. Natl. Acad. Sci. U. S. A.* 102, 7612–7617
4 Galloway, J.N. *et al.* (2004) Nitrogen cycles: past, present, and future. *Biogeochemistry* 70, 153–226
5 Bennett, E.M. *et al.* (2001) Human impact on erodable phosphorus and eutrophication: a global perspective. *Bioscience* 51, 227–234
6 Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Synthesis,* Island Press
7 Comprehensive Assessment of Water Management in Agriculture (2007) *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture,* Earthscan Publications
8 Carpenter, S.R. *et al.* (2006) Millennium ecosystem assessment: research needs. *Science* 314, 257–258
9 Peterson, G.D. *et al.* (2003) Uncertainty and the management of multistate ecosystems: an apparently rational route to collapse. *Ecology* 84, 1403–1411
10 Folke, C. *et al.* (2004) Regime shifts, resilience, and biodiversity in ecosystem management. *Ann. Rev. Ecol. Evol. Syst.* 35, 557–581
11 Gunderson, L. and Holling, C., eds (2002) *Panarchy: Understanding Transformations in Human and Natural Systems*, Island Press
12 Peters, D.P.C. *et al.* (2004) Cross-scale interactions, nonlinearities, and forecasting catastrophic events. *Proc. Natl. Acad. Sci. U. S. A.* 101, 15130–15135

13 Rial, J.A. *et al.* (2004) Nonlinearities, feedbacks and critical thresholds within the Earth's climate system. *Clim. Change* 65, 11–38
14 Rietkerk, M. *et al.* (2004) Self-organized patchiness and catastrophic shifts in ecosystems. *Science* 305, 1926–1929
15 Scheffer, M. *et al.* (2001) Catastrophic shifts in ecosystems. *Nature* 413, 591–596
16 Walker, B. and Meyers, J.A. (2004) Thresholds in ecological and social-ecological systems: a developing database. *Ecol. Soc.* 9, 3
17 Scheffer, M. *et al.* (2005) Synergy between small- and large-scale feedbacks of vegetation on the water cycle. *Glob. Change Biol.* 11, 1003–1012
18 Ripl, W. (2003) Water: the bloodstream of the biosphere. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 358, 1921–1934
19 Carpenter, S.R. (2003) *Regime Shifts in Lake Ecosystems: Pattern and Variation,* Ecology Institute
20 Carpenter, S.R. (2005) Eutrophication of aquatic ecosystems: bistability and soil phosphorus. *Proc. Natl. Acad. Sci. U. S. A.* 102, 10002–10005
21 Diaz, R.J. (2001) Overview of hypoxia around the world. *J. Environ. Qual.* 30, 275–281
22 Donner, S.D. and Scavia, D. (2007) How climate controls the flux of nitrogen by the Mississippi River and the development of hypoxia in the Gulf of Mexico. *Limnol. Oceanogr.* 52, 856–861
23 Scheffer, M. and van Nes, E.H. (2007) Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. *Hydrobiologia* 584, 455–466
24 Hooke, J. (2003) River meander behaviour and instability: a framework for analysis. *Trans. Inst. Brit. Geograph.* 28, 238–253
25 Knox, J.C. (2006) Floodplain sedimentation in the Upper Mississippi Valley: natural versus human accelerated. *Geomorphology* 79, 286–310
26 Simon, A. and Rinaldi, M. (2006) Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. *Geomorphology* 79, 361–383
27 Dent, C.L. *et al.* (2002) Multiple states in river and lake ecosystems. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 257, 635–645
28 Peters, D.P.C. *et al.* (2006) Disentangling complex landscapes: new insights into arid and semiarid system dynamics. *Bioscience* 56, 491–501
29 Ludwig, J.A. *et al.* (2005) Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* 86, 288–297
30 Kefi, S. *et al.* (2007) Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature* 449, 213–217
31 Sankaran, M. *et al.* (2005) Determinants of woody cover in African savannas. *Nature* 438, 846–849
32 Cramer, V.A. and Hobbs, R.J. (2005) Assessing the ecological risk from secondary salinity: a framework addressing questions of scale and threshold responses. *Austral. Ecol.* 30, 537–545
33 Anderies, J.M. *et al.* (2006) Loss of resilience, crisis, and institutional change: lessons from an intensive agricultural system in southeastern Australia. *Ecosystems (N. Y., Print)* 9, 865–878
34 Fernandez, R.J. *et al.* (2002) Degradation and recovery in socio-ecological systems. In *Global Desertification: Do Humans Cause Deserts?* (Reynolds, J.F. and Smith, D.M.S., eds), pp. 297–323, Dahlem University Press
35 Bossio, D. *et al.* (2007) Conserving land – protecting water. In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management* (Molden, D., ed.), pp. 551–583, Earthscan
36 Enfors, E.I. and Gordon, L.J. (2007) Analysing resilience in dryland agro-ecosystems: a case study of the Makanya catchment in Tanzania over the past 50 years. *Land Degrad. Dev.* 18, 680–696
37 Antle, J.M. *et al.* (2006) Multiple equilibria, soil conservation investments, and the resilience of agricultural systems. *Environ. Dev. Econ.* 11, 477–492
38 Makarieva, A.M. and Gorshkov, V.G. (2007) Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrol. Earth Syst. Sci.* 11, 1013–1033
39 Feddema, J.J. *et al.* (2005) The importance of land-cover change in simulating future climates. *Science* 310, 1674–1678
40 Higgins, P.A.T. *et al.* (2002) Dynamics of climate and ecosystem coupling: abrupt changes and multiple equilibria. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 357, 647–655
41 Sternberg, L.D.L. (2001) Savanna-forest hysteresis in the tropics. *Glob. Ecol. Biogeogr.* 10, 369–378
42 Foley, J.A. *et al.* (2003) Regime shifts in the Sahara and Sahel: interactions between ecological and climatic systems in northern Africa. *Ecosystems (N. Y., Print)* 6, 524–539
43 Dekker, S.C. *et al.* (2007) Coupling microscale vegetation-soil water and macroscale vegetation-precipitation feedbacks in semiarid ecosystems. *Glob. Change Biol.* 13, 671–678
44 Los, S.O. *et al.* (2006) An observation-based estimate of the strength of rainfall-vegetation interactions in the Sahel. *Geophys. Res. Lett.* 33, DOI: 10.1029/2006GL027065 (http://www.agu.org/journals/gl)
45 Oyama, M.D. and Nobre, C.A. (2003) A new climate-vegetation equilibrium state for tropical South America. *Geophys. Res. Lett.* 30, DOI: 10.1029/2003GL018600 (http://www.agu.org/journals/gl)
46 Hutyra, L.R. *et al.* (2005) Climatic variability and vegetation vulnerability in Amazonia. *Geophys. Res. Lett.* 32, DOI: 10.1029/2005GL024981 (http://www.agu.org/journals/gl)
47 Cowling, S.A. and Shin, Y. (2006) Simulated ecosystem threshold responses to co-varying temperature, precipitation and atmospheric CO_2 within a region of Amazonia. *Glob. Ecol. Biogeogr.* 15, 553–566
48 Nepstad, D. *et al.* (2004) Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. *Glob. Change Biol.* 10, 704–717
49 Zickfeld, K. *et al.* (2005) Is the Indian summer monsoon stable against global change? *Geophys. Res. Lett.* 32, DOI: 10.1029/2005GL022771 (http://www.agu.org/journals/gl)
50 Miller, G. *et al.* (2005) Sensitivity of the Australian monsoon to insolation and vegetation: implications for human impact on continental moisture balance. *Geology* 33, 65–68
51 del-Val, E. *et al.* (2006) Rain forest islands in the Chilean semiarid region: fog-dependency, ecosystem persistence and tree regeneration. *Ecosystems (N. Y., Print)* 9, 598–608
52 Dawson, T.E. (1998) Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecologia* 117, 476–485
53 D'Almeida, C. *et al.* (2007) The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *Int. J. Climatol.* 27, 633–647
54 Elmqvist, T. *et al.* (2003) Response diversity, ecosystem change, and resilience. *Front. Ecol. Environ.* 1, 488–494
55 Lundberg, J. and Moberg, F. (2003) Mobile link organisms and ecosystem functioning: implications for ecosystem resilience and management.. *Ecosystems (N. Y., Print)* 6, 87–98
56 Peterson, G.D. (2002) Estimating resilience across landscapes. *Cons. Ecol.* 6, 17
57 Nowak, P. *et al.* (2006) Disproportionality as a framework for linking social and biophysical systems. *Soc. Nat. Resour.* 19, 153–173
58 Sharpley, A.N. *et al.* (2001) Assessing site vulnerability to phosphorus loss in an agricultural watershed. *J. Environ. Qual.* 30, 2026–2036
59 Janssen, M.A. *et al.* (2004) Robust strategies for managing rangelands with multiple stable attractors. *J. Environ. Econ. Manag.* 47, 140–162
60 Holmgren, M. *et al.* (2006) Extreme climatic events shape arid and semiarid ecosystems. *Front. Ecol. Environ.* 4, 87–95
61 Carpenter, S.R. and Brock, W.A. (2006) Rising variance: a leading indicator of ecological transition. *Ecol. Lett.* 9, 308–315
62 Folke, C. *et al.* (2005) Adaptive governance of social-ecological systems. *Ann. Rev. Environ. Res.* 30, 441–473
63 Scheffer, M. and Carpenter, S.R. (2003) Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol. Evol.* 18, 648–656
64 Food and Agriculture Organization of the United Nations (2007) FAOSTAT Database on Agriculture, FAO (http://faostat.fao.org)
65 Rockstrom, J. *et al.* (2007) Assessing the water challenge of a new green revolution in developing countries. *Proc. Natl. Acad. Sci. U. S. A.* 104, 6253–6260
66 Rockstrom, J. and Barron, J. (2007) Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. *Irrig. Sci.* 25, 299–311
67 Reynolds, J.F. *et al.* (2007) Global desertification: building a science for dryland development. *Science* 316, 847–851
68 Delire, C. *et al.* (2004) Long-term variability in a coupled atmosphere-biosphere model. *J. Clim.* 17, 3947–3959
69 Koster, R.D. *et al.* (2004) Regions of strong coupling between soil moisture and precipitation. *Science* 305, 1138–1140