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VEGETATION PATCHES AND RUNOFF–EROSION AS INTERACTING ECOHYDROLOGICAL PROCESSES IN SEMIARID LANDSCAPES

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Abstract. Ecological and hydrological processes can interact strongly in landscapes, yet these processes are often studied separately. One particularly important interaction between these processes in patchy semiarid lands is how vegetation patches serve to obstruct runoff and then how this retained water increases patch growth that, in turn, provides feedbacks to the system. Such ecohydrological interactions have been mostly demonstrated for semiarid landscapes with distinctly banded vegetation patterns. In this paper, we use data from our studies and from the literature to evaluate how strongly four ecohydrological interactions apply across other patchy semiarid vegetations, and how these interactions are affected by disturbances. We specifically address four questions concerning ecohydrological interactions: (1) if vegetation patches obstruct runoff flows during rainfall events, how much more soil water is stored in these patches compared to open interpatch areas; (2) if inputs of water are higher in patches, how much stronger is the pulse of plant growth compared to interpatches; (3) if more soil water in patches promotes greater biological activity by organisms such as earthworms that create macropores, how much does this improve soil infiltrability; and (4) if vegetation patches are damaged on a hillslope, how much does this increase runoff and erosion and decrease biomass production? We used the trigger–transfer–reserve–pulse framework developed for Australian semiarid woodlands to put these four questions into a landscape context. For a variety of patchy semiarid vegetation types in Australia, Europe, and North America, we found that patches significantly stored more soil water, produced more growth and had better infiltrability than interpatches, and that runoff and erosion can markedly increase on disturbed hillslopes. However, these differences varied greatly and appeared to depend on factors such as the intensity and amount of input events (rainstorms) and type of topography, soils, and vegetation. Experimental and modeling studies are needed to better quantify how these factors specifically affect ecohydrological interactions. Our current findings do support the conclusion that vegetation patches and runoff–erosion processes do strongly interact in many semiarid landscapes across the globe, not just banded landscapes.

Key words: hydrology; landscape ecology; landscape function; runoff; soil erosion.

SPECIAL FEATURE

INTRODUCTION

Semiarid landscapes function as strongly coupled ecological–hydrological systems, including horizontal and vertical flows and interactions across fine to coarse scales (Wilcox et al. 2003*a*, Belnap et al. 2004, Seyfried et al. 2004). One particularly important interaction is how, during rainstorms, patches of vegetation serve as surface obstructions that slow and trap runoff, sediments, and nutrients from open interpatch areas (Wilcox and Breshears 1995, Tongway and Ludwig 1997, Schlesinger et al. 2000, Wilcox et al. 2003*a*). In semiarid landscapes, these surface obstructions can include logs, rocks, and ant and termite mounds, but more typically are distinct patches of vegetation with sufficient stem and biomass densities to trap water- and wind-borne sediments and litter (Tongway and Ludwig 1997). These vegetation patches can vary from small clumps of grasses (e.g., 0.5–2 m^2) to large groves of mulga (*Acacia aneura*) trees (e.g., 100–1000 m^2), such as those observed in central Australia (Dunkerley 2002). Further, the inputs of water and nutrients to the patch can produce an enhanced pulse of plant growth. In turn, the new vegetative or structural biomass (e.g., woody stems) should maintain, or even increase, the capacity of the patch to obstruct overland flows in the

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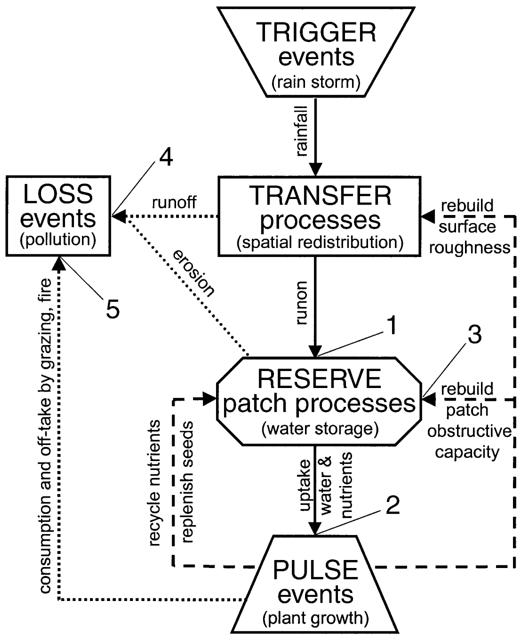

FIG. 1. The trigger–transfer–reserve–pulse (TTRP) framework linking temporal (trigger) events, such as rainstorm inputs of water, through spatial transfer (runoff–runon) and reserve (patch) processes, to pulse events, such as plant growth. These linkages are denoted with solid arrows. Feedbacks and flows out of the system are indicated with dashed or dotted arrows. The five numbers refer to positions in this framework where we specifically evaluated key interactions between ecological and hydrological events and processes.

next rainstorm event. Such coupled and interacting ecohydrologicalal processes have been documented in field and modeling studies in semiarid banded landscapes where vegetation occurs in distinct, repeating arcs and stripes called tiger bush (see papers in Tongway et al. [2001]). There is some evidence from other field studies and resource redistribution models that such coupled ecohydrological processes operate in other kinds of patchy semiarid landscapes, not just in banded vegetation (van de Koppel et al. 1997, Adler et al. 2001, Wilcox et al. 2003*a*). However, there is a need to provide further evidence for the strength of such ecohydrological interactions in patchy, but nonbanded, semiarid landscapes.

Given the complexity of ecohydrological interactions, frameworks have proven to be useful tools for conceptualizing and synthesizing complex interactions between landscape patterns and processes (e.g., Wilcox and Breshears 1995, Breshears and Barnes 1999, Roth 2004). In particular, the trigger–transfer–reserve–pulse (TTRP) conceptual framework (Fig. 1) is useful for connecting the redistribution of runoff to landscape patch patterns and processes (Ludwig et al. 1997, Ludwig and Tongway 2000). This TTRP framework was specifically developed to explain ecological patterns for banded semiarid rangelands in eastern Australia (Ludwig and Tongway 1995). Some of the fundamental explicit and implicit assumptions of this framework have been tested and clarified for nonbanded semiarid landscapes outside of Australia (Wilcox et al. 2003*a*). Here, we use this TTRP framework to help organize our evaluation of ecohydrological interactions for nonbanded semiarid landscapes.

In this paper, we first briefly describe the TTRP framework and how it depicts key spatial and temporal interactions between rainfall events, landscape patch structures and responses, and runoff–erosion processes, and how these change with disturbances. Then, using this framework and ecological and hydrological data from our own and other studies, we specifically address four questions concerning the strength of ecohydrologic interactions for patch semiarid landscapes, providing data examples at two spatial scales: vegetation patch and hillslope. At the vegetation patch scale, three questions are evaluated. First, if robust patches of perennial plants obstruct flows of runoff during rainfall events, how much more soil water is stored in these patches compared to open interpatches characterized by annual plants and bare soil? Second, if more water is available in these perennial patches, how much larger is its pulse of plant growth (biomass) and, third, is infiltrability also greater in these patches due to this growth and other biological activities? At the hillslope scale, a fourth interaction is evaluated. If grazing degrades vegetation patches over a hillslope, how much does this increase runoff and sediment yields and decrease forage biomass production?

This paper focuses on surface or horizontal flows of water (runoff), and their ecohydrological interactions across semiarid landscapes, at vegetation patch–interpatch and hillslope scales. A companion paper also deals with horizontal flows and interactions across semiarid landscapes, but focuses on nutrients and finer plant patch–interpatch (soil crust) scales (Belnap et al. 2004). For brevity, vertical flows of water, including deep drainage, are not evaluated here, but are covered in another paper in this volume (Seyfried et al. 2004), and elsewhere (e.g., Walvoord et al. 2002). Although beyond the scope of this paper, surface winds also trigger important ecological interactions in semiarid landscapes (see Breshears et al. 2003).

THE TRIGGER–TRANSFER–RESERVE–PULSE (TTRP) FRAMEWORK

Semiarid landscapes exhibit a great deal of spatial and temporal variability, making synthesis of related processes and patterns challenging. The TTRP framework provides a structure for depicting links and interactions between ecological and hydrological events and processes (Fig. 1), and shows where disturbances can modify these interactions (Ludwig et al. 1997, Ludwig and Tongway 2000).

The trigger and pulse components of the TTRP framework can be viewed as largely temporal events (Fig. 1). For example, a rainstorm can be viewed as a

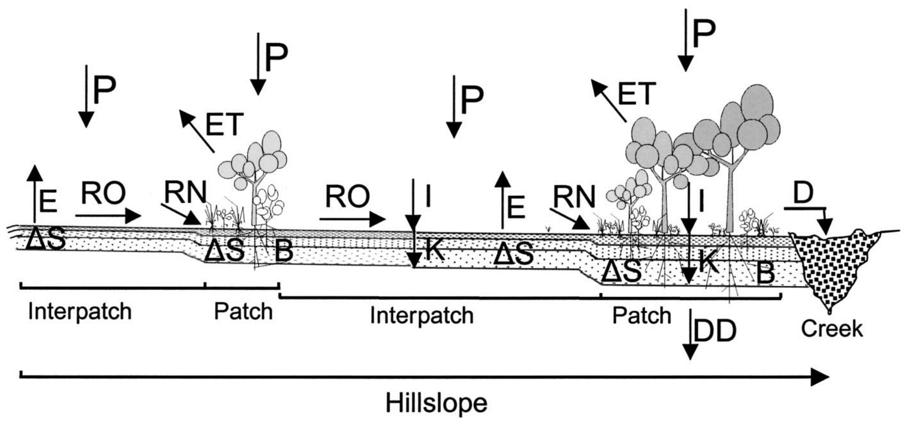

FIG. 2. Diagram illustrating hydrological and ecological events and processes occurring down a gentle hillslope. Precipitation events (P) can trigger runoff (RO) from small and large interpatches, which can be captured as runon (RN) by vegetation patches and stored in soil layers (ΔS) at rates dependent on soil infiltration (I) and hydraulic conductivity (K) properties and levels of biological activity (B). As illustrated, soil water storage (ΔS) is usually deeper under larger vegetation patches. Soil water is lost by deep drainage (DD), surface evaporation (E), and plant evapotranspiration (ET). During larger precipitation events, runoff may discharge (D) into creeks and rivers.

trigger that inputs water to a landscape system over a brief period, either as a large single event or a series of smaller events. This precipitation (P), falling on vegetation patches and open interpatches on hillslopes (Fig. 2), triggers the infiltration of water (I) into the soil surface, where it may move into deeper soil layers by drainage processes depending on soil hydraulic conductivity properties (K). This water may deeply drain (DD) out of the soil profile. If intensities during a rainfall event, along with related water input events such as stemflow (e.g., Martinez-Mesa and Whitford 1996), exceed soil infiltration capacities, runoff (RO) occurs, which may be trapped and retained by a nearby vegetation patch as runon (RN), adding to soil water stores (ΔS). Soil water in bare interpatches is evaporated (E), but within vegetation patches it is largely evapo-transpired (ET) during pulses of plant growth (Fig. 1). Water stored in soil layers (ΔS, Fig. 2) also promotes biological activity (B) by organisms such as soil invertebrates to form soil aggregates and macropores, thus enhancing infiltrability, particularly within vegetation patches.

Runoff water (RO) flowing over the landscape surface (Fig. 2) may be discharged from the system (D), carrying suspended sediments that can pollute creeks in the catchment. Thus, transfers and reserves in the TTRP framework can be viewed as mainly spatial processes (Fig. 1), the emphasis being on what happens over space—e.g., overland flows on a hillslope (although these processes obviously also take place over time).

This framework also depicts other very important coupled ecohydrological processes. For example, a pulse of plant growth replenishes seeds and returns litter as organic matter and nutrients for recycling to the patch reserve. This pulse of growth also contributes to the maintenance of patch structures (e.g., stems), perhaps even increasing these structures (e.g., higher stem densities), so that the vegetation patch enhances its hydrological function in the next trigger event by more efficiently obstructing overland flows of water. However, this plausible and likely very important ecohydrological feedback needs to be verified for patchy semiarid landscape systems as such data are currently lacking.

Another useful aspect of the TTRP framework is its inclusion of the effects of consumptive disturbances, such as grazing and fire, on the functioning of the system (Fig. 1). As noted earlier, the cover (and spatial arrangement) of vegetation patches on a hillslope determines the potential for that landscape to obstruct flows of water (and wind) and thereby trap and retain vital water and soil resources (Tongway and Ludwig 1997). If semiarid landscapes are intensively grazed and repeatedly burned over a number of years and decades, the cover and size of vegetation patches is greatly reduced, which decreases their effectiveness as obstructions for trapping and retaining resources, thereby increasing runoff and erosion (Greene et al. 1994, Scanlan et al. 1996*a*, van de Koppel et al. 1997, Calvo-Cases et al. 2003).

EVALUATING ECOHYDROLOGICAL INTERACTIONS

Interaction 1: vegetation patches obstruct runoff and store runon

The first interaction evaluated is, if vegetation patches obstruct runoff flow, how much more water is stored as runon in these patches compared to upslope interpatch areas (Fig. 1, #1; Fig. 2, RO, RN, ΔS). Using multiple-scale runoff measurements for three plots located between trees (intercanopy) in semiarid piñon–juniper (*Pinus edulis–Juniperus monosperma*) woodland in New Mexico, Reid et al. (1999) found that,

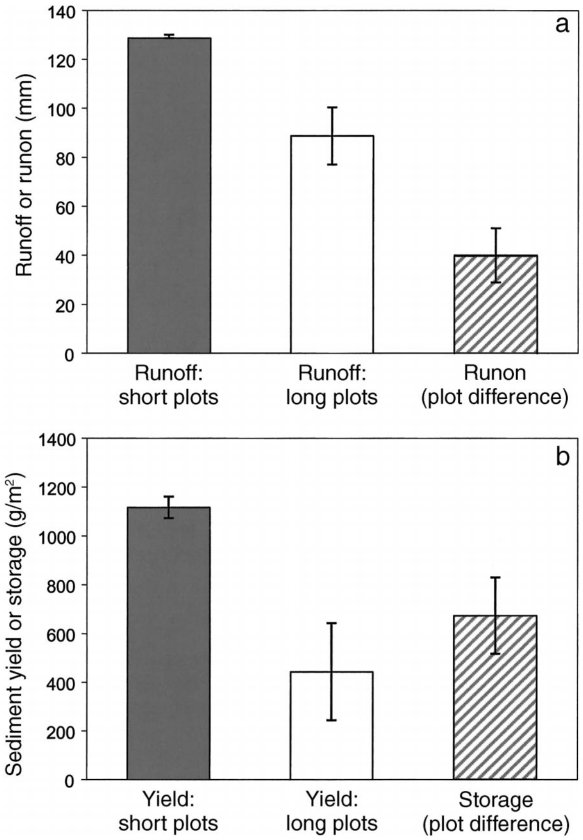

FIG. 3. Mean (±1 SE) values for (a) runoff and runon, and (b) sediment yield and storage from short and long collection plots located between tree canopies (intercanopy plots) in semiarid woodlands in northern New Mexico. These collection data are from large convective storms occurring over the period from July 1994 to August 1996 (see Reid et al. [1999] for experimental details).

during and after large convective storms (i.e., significant rainfall events), accumulative runoff from short, contiguous subplots averaged about 130 mm (Fig. 3a), whereas runoff from one longer adjacent subplot (equal in area to the shorter subplots) averaged only about 90 mm. The difference between these two means (40 mm) is an estimate of runon—that is, the amount of runoff captured and stored within the long subplot. Field observations indicated that it was the vegetation clumps or patches within the long subplots that had trapped and stored significant amounts of runoff water as runon.

These findings have been confirmed by further multiple-scale runoff experiments in these semiarid piñon–juniper woodlands (Wilcox et al. 2003*a*). Similar findings were reported by Bergkamp (1998), who conducted multiple-scale runoff experiments using a rainfall simulator (70 mm/h for 30 min) in semiarid oak (*Quercus* sp.) woodlands of central Spain: any water ponding on bare interpatch areas rapidly began to flow as runoff and then infiltrated as runon in downslope thyme (*Thymus* sp.) bush patches.

It is interesting to note that Reid et al. (1999) also measured sediment yields and found that 675 g/m² of sediment was captured or stored within the long subplot (Fig. 3b), indicating that vegetation patches also trap sediments flowing in runoff. They also found that runoff and sediment yields were quite variable in space (plot to plot) and through time—yields were much lower for gentler frontal and small winter storms, as might be expected.

Other kinds of semiarid landscape studies also support the fact that vegetation patches obstruct and store significant amounts of runoff as runon. For example, depth-of-wetting-front data illustrates the role of the plants, soils, litter, and biota under small groves of mulga trees (*Acacia aneura*) in enhancing the storage of runoff water as runon (Fig. 4). After 50 mm of rain, falling in a series of summer storms over a week in February 2003, soil wetting was much deeper under mulga groves than in the intergroves (T. Ellis and J. Brophy, *unpublished data*). These runoff–runon data were measured along a 35-m transect at ''Lake Mere'' in New South Wales, Australia, and support earlier hypotheses on the role of ecohydrological processes in these patchy semiarid woodlands (Ludwig and Tongway 1995). Soil wetting-front data for inside and outside vegetation patches on semiarid landscapes in central New Mexico following rainfall events also provides evidence for this ecohydrological interaction (Bhark and Small 2003).

Interaction 2: runon enhances plant growth pulses

If vegetation patches effectively obstruct runoff from interpatches and store water as runon, as documented above, potentially more soil water is available for a pulse of plant growth in these patches compared to adjacent interpatches (Fig. 1, #2). In other words, the hydrological process of runoff–runon is linked to an ecological function, plant growth. Thus, we should observe greater biomass production by plants within vegetation patches than by plants located in open interpatches because of the greater soil water storage under

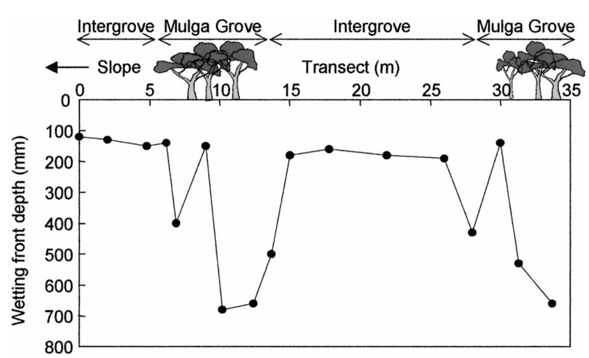

FIG. 4. Depth of the wetting front (mm) in soils along a 35-m transect cutting downslope (right to left) through small groves of mulga (*Acacia aneura*) trees and across open intergroves.

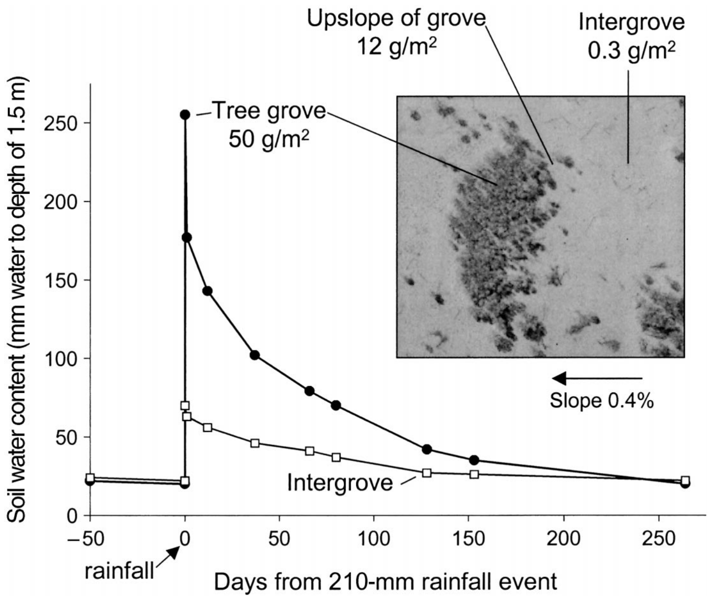

FIG. 5. Soil water contents (millimeters of water to a depth of 1.5 m) and aboveground herbage biomass (g/m^2) under mulga (*Acacia aneura*) groves and in intergrove areas following a 210-mm rainfall event in central Australia semiarid woodlands (data from Goodspeed and Winkworth [1978] and Winkworth [1983]).

vegetation patches (Fig. 2, ΔS) after significant rainfall events, and also because of local microclimate effects such as reduced vapor flux (Fig. 2, ET) and cooler soils due to litter (Breshears et al. 1998).

In the mulga woodlands located on the Burt Plains 30 km northwest of Alice Springs, central Australia, Winkworth (1983) found that a 210 mm rainfall event in early March 1972 wet the soils under a grove of mulga trees equivalent to 255 mm of water to a depth of 1.5 m, which rapidly declined after one day to hold the equivalent of 177 mm of water (Fig. 5). Using this stored water, plants under the mulga tree grove produced an estimated biomass pulse of 50 g/m^2. Only 63 mm of soil water was held to 1.5 m after one day in the soils of the intergroves, which subsequently produced a herbage biomass pulse of $<$1 g/m^2. Areas immediately upslope of the groves produced a pulse of 12 g/m^2. All soils in the landscape held about 20–25 mm of water to 1.5 m prior to the 210-mm rainfall event. After 264 days, soil water had attenuated back down to 20–25 mm and was roughly equal in both the mulga grove patches and the open interpatches.

More recent results from a research site in the mulga woodlands of eastern Australia confirms this interaction (Noble et al. 1998), where, four weeks following a 43-mm rainfall event in November 1992 that generated significant runoff–runon, aboveground herbage production in open intergroves (runoff areas) was only 0.3 g/m^2 compared to 65 g/m^2 under the mulga groves and 124 g/m^2 at the upslope edge of these groves (runon zones). Over a six-year period (1988–1993), herbage production within runon landscape zones on this site was consistently greater than that for runoff areas (Hodgkinson and Freudenberger 1997). Tiger bush in southwestern Niger, Africa, also confirms this interaction (Hiernaux and Gerard 1999), where the average aboveground herbage production on runoff slopes was only 2.5 g/m^2 compared to 43.0 g/m^2 for runon areas under bush thickets.

Interaction 3: vegetation patches enhance soil infiltrability

In addition to having enhanced pulses of plant growth, as documented above, patches have other kinds of pulses of biological activity. For example, macroinvertebrates such as termites, ants, and earthworms are very active within the perennial vegetation of semiarid landscapes (Dawes-Gromadzki and Spain 2003). This biological activity improves soil aggregation and macroporosity, and hence the infiltrability of the soil (Imeson et al. 1998). In the TTRP framework, these enhanced biological and soil processes can improve the ability of vegetation patches to obstruct, capture, and store runoff water as runon in the next significant rainfall event (Fig. 1, #3). Therefore, we should observe higher infiltrability rates under perennial vegetation patches than in interpatch areas.

Evidence supporting this ecohydrological interaction comes from the semiarid eucalypt savannas of northeast Australia (Roth et al. 2003). Vegetation patches within an ungrazed cattle and kangaroo exclosure with highly friable and biologically active soils, rich in earthworm castings and ant and termite nests, had a mean infiltration rate exceeding 75 mm/h (Table 1), which was the maximum rate that could be determined from the rainfall simulator used. In sharp contrast, open areas with cattle grazing, no biological crusts, and with signs of active erosion, had infiltration rates of only 13 mm/h.

Additional evidence comes from the mulga woodlands of central Australia, where Dunkerley (2002) found infiltration rates as high as 292 mm/h under a

TABLE 1. Mean infiltration rates (mm/h) for relatively undisturbed vegetated patches under canopies and in intercanopies, and for disturbed intercanopies in semiarid eucalypt savannas and mulga woodlands, Australia, and in semiarid piñon–juniper woodlands, North America.

Site	Undisturbed, vegetated patches: Canopy	Undisturbed, vegetated patches: Inter-canopy	Disturbed inter-canopy
Eucalypt savanna†	>75	53	13
Mulga woodland‡	292	18	16
Piñon–juniper woodland§	150	93	51

† Infiltration rates are based on rainfall simulator studies (Roth et al. 2003).

‡ Infiltration rates are based on 10-cm single-ring infiltrometer studies (Dunkerley 2002).

§ Infiltration rates are estimated from saturated hydraulic conductivity studies (Wilcox et al. 2003*b*).

mulga canopy near the stem where the soils were highly friable and enriched with organic matter and biological activity (Table 1). However, in vegetated areas just outside tree canopies, infiltration rates were much lower and differed little from those in disturbed, bare interpatch spaces (18 vs. 16 mm/h, respectively). In semiarid piñon–juniper woodlands of northern New Mexico, where saturated hydraulic conductivity (used to estimate infiltration capacity) was measured at 74 locations in the field using a ponded infiltrometer (Wilcox et al. 2003*b*), infiltration capacities averaged 150 mm/h under piñon and juniper tree canopies, 93 mm/h in vegetated intercanopies (mostly small patches of blue grama, *Bouteloua gracilis*), and only 51 mm/h in intercanopies with bare soil. These mean infiltration capacities were highly variable within both canopy and intercanopies, and studies have demonstrated that enhanced infiltrability can extend well beyond the edge of plant canopies (Seyfried and Wilcox 1995, Schlesinger et al. 1999, Dunkerley 2002). These findings suggest (as do other studies, e.g., Wilcox et al. 2003*a*) that other factors, such as litter under canopies, the extension of roots from canopies into intercanopies, and the surface roughness of vegetated intercanopies, also play a significant role in controlling runoff–runon processes, and these factors need to be included in ecohydrological studies.

Interaction 4: disturbances affect hillslope losses

If the cover of perennial vegetation patches, hence the amount of surface obstruction, is significantly reduced on a hillslope because of disturbances, then runoff and sediment losses are likely to increase markedly during rain storms (Fig. 1, #4). This ecohydrological interaction is supported by data from runoff plots located on disturbed and undisturbed hillslopes in semiarid piñon–juniper woodlands in New Mexico (Wilcox et al. 2003*a*), where mean annual runoff from disturbed hillslopes was almost twice that of relatively undisturbed hillslopes (Table 2). Mean annual sediment yields from these disturbed plots were more than three times those from undisturbed plots.

Similar results were found for eucalypt savannas in northeast Australia (Table 2), where runoff and erosion

TABLE 2. Mean annual runoff (mm), mean annual sediment yields (kg/ha), and mean aboveground herbage biomass (g/m²) for undisturbed vs. disturbed hillslopes in semiarid piñon–juniper woodlands, North America, and eucalypt savannas, Australia.

Site	Annual runoff (mm)		Annual sediment yield (kg/ha)		Herbage biomass (g/m²)	
	Undisturbed	Disturbed	Undisturbed	Disturbed	Undisturbed	Disturbed
Piñon–juniper woodland†	30	53	314	1012	ND	ND
Eucalypt savanna‡, §	168	160	1240	1760	225	85
Eucalypt savanna‖, ¶	34	43	230	373	246	92

Note: ND = not determined.

† Mean yearly runoff and sediment yields were collected from 1991 to 1998 on four adjacent 3.0 × 10.7 m plots located on a piñon–juniper woodland hillslope (Reid et al. 1999, Wilcox et al. 2003*a*). Two of the plots were undisturbed controls and two were disturbed by removing or altering their surface cover (i.e., vegetation, litter, rocks, and soil crusts).

‡ Mean July to June runoff and total sediment yields are based on hillslope collections in 10 m wide troughs for ~25 m upslope, for three periods between mid-1987 and mid-1990 (wet season: November–March) in lightly grazed (relatively undisturbed) and heavily grazed (disturbed) paddocks characterized by *Eucalyptus* trees and perennial tussock grasses (McIvor et al. 1995).

§ Aboveground herbage biomass values are based on BOTANAL (Tothill et al. 1978) yield estimates for 48 quadrats (50 × 50 cm) in each site (McIvor et al. 1995).

‖ Mean annual runoff and bedload sediment yields are based on collections from hillslope troughs in grazed (disturbed) paddocks dominated by *Heteropogon contortus* and in undisturbed exclosures within these paddocks, over six years, 1986–1991 (Scanlan et al. 1996*a*).

¶ The BOTANAL method was also used to estimate aboveground herbage biomass in 50 quadrats (50 × 50 cm) in each experimental plot from 1985 to 1990. Data are from paddocks dominated by both *Heteropogon contortus* and *Bothriochloa pertusa* (see Scanlan et al. 1996*b*: Fig. 4).

were measured on experimental runoff plots located on relatively undisturbed (ungrazed or lightly grazed) and disturbed (heavily grazed) hillslopes (McIvor et al. 1995, Scanlan et al. 1996*a*). These studies found that, although mean annual runoff did not differ greatly between cattle-grazed and ungrazed hillslopes, the amount of sediment moved as bedload per year was much greater from grazed hillslopes.

If runoff and soil losses from a hillslope are high because of a long-term heavy use of vegetation patches by livestock (i.e., consumptive off-take; Fig. 1, #5), then less water and nutrients are available for plant growth and biomass production should be lower on disturbed hillslopes than on undisturbed slopes. Data on biomass production from the same eucalypt savanna hillslopes where runoff and sediment data were collected (Table 2) document that, for two different studies in northeast Australia (McIvor et al. 1995, Scanlan et al. 1996*b*), mean annual aboveground production of herbage (grasses + forbs) was more than 2.5 times lower on those hillslopes affected by long-term cattle grazing. This indicates a strong ecohydrological link between runoff and soil losses and lower biomass production.

Implications and Research Challenges

Our evaluation of four interactions between ecological and hydrological events and processes at vegetation patch–interpatch and hillslope scales confirms that these interactions are strong for many kinds of patchy semiarid landscapes, not just banded landscapes as previously documented (see papers in Tongway et al. [2001]). At these scales, the role of patches in semiarid landscapes continues to be actively evaluated in Australia (e.g., Dunkerley 2002, Scanlan 2002, Roth 2004), in Europe (e.g., Cammeraat and Imeson 1999, Calvo-Cases et al. 2003), and in North America (e.g., Bhark and Small 2003, Wilcox et al. 2003*a*). However, ecohydrological interactions can have profound effects and management implications at larger watershed and catchment scales, not just at local vegetation patch–interpatch and hillslope scales. If suspended sediments are exported from disturbed hillslopes and discharged into creeks and rivers (Fig. 2), downstream environmental effects on, for example, water quality and biota, can be very significant (e.g., Townsend and Douglas 2000, Burrows and Butler 2001). If these sediments are discharged into estuaries, offshore environmental, economic, and social impacts can be far-reaching (e.g., sediment pollution of the Great Barrier Reef leading to reduced tourism [Prosser et al. 2001]). Research is needed to better understand the linkages between ecological and hydrological events and processes across all these scales, from patches on hillslopes to catchments, and to offshore estuaries and reefs.

Conducting such interdisciplinary, multiscale research presents some huge challenges. For example, whereas hydrologists have measured the effect of large vs. small rainfall events on runoff and erosion processes (e.g., Prebble and Stirk 1988, Abrahams et al. 2001), integrated studies by ecologists and hydrologists are needed to better understand how large vs. small events affect these processes and their interactions with vegetation patches across scales (e.g., Reid et al. 1999, Wilcox et al. 2003*a*). A challenging question that remains largely unanswered is how large must rainfall events be to trigger plant growth pulses (e.g., Sala and Lauenroth 1982), which, in this context, are large enough to significantly increase stem densities in patches so that these patches more effectively capture runoff in the next rain event. This landscape process, highlighted in the TTRP framework (Fig. 1; #3), has not been quantified, but is likely to be a very important ecohydrological feedback in patchy semiarid systems.

Further ecohydrologic studies are needed to better understand the connection between the addition of water captured by vegetation patches as runon and enhanced patch and hillslope infiltrability and biomass production. Such coupled processes present difficult research challenges. For example, we need to know if roots and enhanced macroinvertebrate activity and soil porosity significantly extend beyond the edges of vegetation patches, particularly for larger patches such as tree and shrub thickets (e.g., Dunkerley 2002). For such woody thickets, we need to know what happens to these ecohydrological processes and their interactions if thickets become denser or encroach onto interpatch areas (e.g., Huxman et al. 2004). We also need to improve our understanding of the role of other factors in regulating the amount of runoff and soil lost from hillslopes—beyond the effects of vegetation patch cover—including factors such as surface roughness and flow tortuosity (Dunne et al. 1991, Wilcox et al. 1996, Abrahams et al. 2001, Dunkerley 2002).

We evaluated ecohydrological interactions in patchy semiarid landscapes with particular reference to long-term, intense disturbances caused by livestock grazing (e.g., consumptive off-take; Fig. 1, #5). We found that this type of grazing strongly affects the interaction between vegetation patch cover and runoff–erosion processes, which is supported by other semiarid land grazing studies (e.g., Greene et al. 1994, McIvor et al. 1995, Trimble and Mendel 1995, van de Koppel et al. 1997, Calvo-Cases et al. 2003). Understanding these interactions has important implications for improving our management of semiarid landscapes. For example, forage production losses can be avoided by using wise livestock management practices to maintain a good cover of perennial vegetation patches on hillslopes (Noble and Brown 1997).

Any disturbance that reduces the long-term effectiveness of vegetation patches to obstruct flows of water and retain vital water and soil resources within semiarid landscapes may reduce ecohydrological functionality. Fire is a common landscape disturbance in semiarid savannas and woodlands that, if frequent and intense, can significantly diminish the cover and size of vegetation patches, thereby modifying hillslope runoff–erosion processes (e.g., Beeson et al. 2001, Johansen et al. 2001). Similarly, the thinning or clearing of trees within a semiarid savanna or woodland landscape will alter its ecohydrological functionality (e.g., Prebble and Strick 1988, Ludwig and Tongway 2002, Wilcox et al. 2003*a*). Further, the encroachment of woodland trees into grasslands also alters ecohydrological processes (Huxman et al. 2004). Understanding the complexities of such dynamic landscape interactions is another research challenge.

We need to continue the development of landscape simulation models that explicitly incorporate, for example, how rainfall events of different sizes and different disturbances—such as grazing, woody encroachment, tree clearing, and fire—affect ecohydrological interactions across space and time (e.g., the SAVANNA-AU model [Liedloff et al. 2001]). Field studies are needed to improve such spatially explicit ecohydrological models. When improved, such models can be used with confidence to explore and predict how different land uses and management practices influence the vegetation on, and runoff and erosion from, semiarid landscapes.

Conclusions

Using data from our multiple-scale runoff-runon experiments and from the literature, we documented that patches of vegetation in semiarid savannas, woodlands, and shrublands in Australia, North America, and Europe obstruct flows and store more water than interpatch areas. Other experiments in these landscapes illustrated that vegetation patches that retained more water had greater pulses of plant growth, hence biomass production, and infiltration capacity than open interpatch areas. At the hillslope scale, we also found that runoff, sediment yield, and vegetation growth were linked so that when the cover of vegetation patches decreased due to grazing, losses of runoff and, especially, sediment increased while forage production decreased. Although all these findings may seem intuitively logical and therefore unsurprising, their strength, importance, and extent are often not fully appreciated, and they support our contention that strong interactions occur between ecological and hydrological events and processes in many patchy semiarid landscapes, not just banded landscapes.

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