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Ecohydrology Bearings — Invited Commentary

Spatial patterns, processes and predictions in ecohydrology: integrating technologies to meet the challenge

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ABSTRACT

Spatial organization is the pre-eminent challenge of ecohydrology as a geospatial science. Ecohydrological patterns emerge as a result of interactions of fine-scale processes and functions that are difficult to observe, quantify and predict. As a result, an integrated approach to the study of spatial patterns in ecohydrology requires a more focused engagement of sampling, sensing and computational tools that are presently available to the scientific community. Here, an incremental and iterative process is proposed consisting of field experiments sequenced with distributed ecohydrological modelling aimed at identifying emergent spatial patterns. In this commentary, three case studies are presented that illustrate how the integration of spatial technologies can provide new insights into the ecohydrological patterns of arid and semiarid ecosystems. The search for emergent ecohydrological behaviour arising from cross-scale interactions can also yield improved process understanding, predictive capabilities and relevance to societal needs.

KEY WORDS spatial organization; sensor networks; remote sensing; numerical modelling; cross-scale interactions; arid and semiarid ecosystems; North American monsoon

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INTRODUCTION

Spatial organization in human and natural systems typically arises from a set of complex interactions occurring over a range of scales. Thus, when spatial patterns emerge, these provoke interest by the general public and scientists in qualitatively describing and quantifying the processes that underlie the patterns (Sivapalan, 2005). In arid and semiarid ecohydrology, examples of spatial organization include clustering of trees in savanna ecosystems (e.g. van Wijk and Rodríguez-Iturbe, 2002), the linkage of plant productivity and channel networks (e.g. Ivanov *et al.*, 2008b) and aspect controls on plant functional types (e.g. Gutiérrez-Jurado *et al.*, 2007), among others. Despite these observable patterns, our interdisciplinary science has yet to tackle spatially explicit interactions in such a way as to provide relevant spatial predictions and understanding to society at large. This is argued to be because of the *limited integration* of current-generation observations and numerical models for resolving the fine-scale processes that lead to organized spatial patterns within natural and human-dominated ecosystems.

A spatial view of ecohydrology is at the forefront of understanding terrestrial and aquatic processes at scales ranging from individual sites (e.g. Loheide *et al.*, 2009; Franz *et al.*, 2011) to entire river basins (e.g. Muneepeerakul *et al.*, 2008; Thompson *et al.*, 2011). Continuing the pace of discoveries and increasing their usefulness for predictions will necessitate an increase in the integration of tools that enable spatial interpretations. Thus, unraveling the principles of spatial organization is a defining challenge for ecohydrology as a *geospatial science*. This commentary focuses attention on the integration of spatial observations and modelling efforts in arid and semiarid ecohydrological systems. Three recent research examples are discussed from forest, subtropical and shrubland ecosystems in south-western North America (Templeton *et al.*, 2010; Mahmood and Vivoni, 2011; Vivoni, 2012). These case studies are intended to illustrate the utility of integrating technologies for studying spatial patterns, processes and functions and to highlight a path-forward for similar ecohydrological studies in other arid and semiarid areas.

INTEGRATION OF SPATIAL OBSERVATIONS AND MODELLING

Fortunately, ecohydrology is developing as a science at an unprecedented time in terms of the availability of new sampling, sensing and computational tools to the community (Jackson *et al.*, 2009). Emerging capabilities in field observations range widely from high-resolution image acquisition by unmanned aerial vehicles (UAVs) (Laliberte

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et al., 2010) to the use of laser spectroscopy in ecohydrological studies (Griffis *et al.*, 2010), among many others. Similarly, advances in computational ecohydrology are providing spatial views on issues ranging from ecosystem state transitions (Bestelmeyer *et al.*, 2011) to the catchment-scale optimization of nutrient, light and water resources by vegetation communities (Hwang *et al.*, 2009). Naturally, new techniques are continually expanding *an ecohydrologist's toolbox*, with the associated imperative to collaborate with scientists and engineers from a wide range of disciplines focused on instrument, sensor network and computational developments (e.g. Rundel *et al.*, 2009).

A key outcome of the fusion of science and engineering in ecohydrology should be a deeper understanding for and improved predictions of spatial patterns, processes and functions in natural and human-dominated landscapes. To achieve this level of integration will require using new technologies to synthesis *new knowledge*, a challenging task in ecohydrology. For example, King and Caylor (2011) document that ecohydrological studies over the past 15 years have rarely linked modelling approaches with process observations or manipulative experiments. This resonates with previous calls for better integration of observational and computational tools in the hydrological and ecological communities (e.g. Kirchner, 2006; Rustad, 2008). As a maturing field, ecohydrology still has the opportunity to seamlessly merge skills from modellers and experimentalists to advance the understanding and prediction of spatial dynamics (Newman *et al.*, 2006). This methodological synthesis can be achieved when hypotheses are framed so that process studies, manipulations and simulation approaches are used in a complementary fashion.

A promising avenue is the use of integrated approaches to understand and predict cross-scale interactions in ecohydrology, where fine-scale processes yield emergent outcomes. For example, Peters *et al.* (2004) describe how erosion processes within soil and plant patches can propagate into widespread woody plant encroachment within historical desert grasslands. The principles of cross-scale interactions outlined by Peters *et al.* (2004) are applicable to other natural and human-dominated systems, including in the following: (a) hydroclimatology and biodiversity of mountain fronts (Vivoni *et al.*, 2010a); (b) riparian groundwater and vegetation disturbances (Martinet *et al.*, 2009); and (c) urban landscaping and climate regulation (Gober *et al.*, 2010). To address cross-scale interactions will require integrating data, models and manipulations that resolve fine-scale processes as well as coarse-scale outcomes. Going from microscopic studies to macroscopic predictions is key as emergent outcomes have direct societal, management and policy implications (e.g. Pataki *et al.*, 2011), in particular when unintended consequences occur.

ILLUSTRATIVE EXAMPLES OF AN INTEGRATIVE APPROACH

Arid and semiarid ecosystems in southwestern North America present a wide array of challenges related to spatial processes, functions and patterns in ecohydrology (Newman *et al.*, 2006; Vivoni *et al.*, 2010b). An important characteristic of the region is the in-phase relation between precipitation and radiation during the summer period because this leads to widespread ecosystem productivity (Vivoni *et al.*, 2008a; Forzieri *et al.*, 2011). In the region, terrestrial, riparian and aquatic ecosystems have organized in response to the pulsed nature of storms during the North American monsoon (NAM). Furthermore, precipitation variations related to the NAM over intra-seasonal to interdecadal time scales have structured the co-evolution of ecological and hydrological dynamics and spatial patterns, with implications on long-term soil and landscape morphology (e.g. Istanbulluoglu *et al.*, 2008; Chorover *et al.*, 2011). Thus, a rich set of open questions in ecohydrology remains on the spatially explicit interactions of climate, soil, terrain and vegetation in this region, in particular in light of climate change-induced disturbances expected in the coming decades (e.g. Williams *et al.*, 2010; Woodhouse *et al.*, 2010).

Given recent knowledge on the ecohydrological interactions during the NAM (Vivoni *et al.*, 2010b), a key next step is to understand cross-scale interactions to provide predictions that are commensurate with water and land management in natural and human-dominated systems. This is achievable through the integration of instruments, sensor networks and computational models applied at scales ranging from hillslopes to large river basins. In practice, however, this integration is hampered by the legacy of individual studies focused on a single aspect. For example, Ivanov *et al.* (2008a) discuss the necessary, but typically absent, field datasets that would allow testing ecohydrological models in a robust, process-oriented fashion. Here, I propose that the ecohydrological research community might most effectively overcome these limitations with an incremental and iterative process where periods of field experimentation are sequenced with model development and testing (Vivoni *et al.*, 2007a). I illustrate this approach of chronological progress from research in the following three ecosystems in southwestern North America: (1) a ponderosa pine hillslope with a historical field study; (2) a subtropical basin with remote sensing fields and sparse ground data; and (3) a shrubland catchment with a dense sensor network and UAV imagery.

Hillslope-scale soil moisture patterns under vertical and horizontal fluxes

As the first step toward the integration of spatial observations and models, a recent modelling assessment (Mahmood and Vivoni, 2011) utilized a field investigation documented by Wilcox *et al.* (1997) and Newman *et al.* (1998) to explore the utility of a distributed model for inferring spatial processes and patterns. The lag between the field and modelling efforts (>10 years) prevented benefitting from the co-implementation of the experimental and computational methods. Despite this, available field data and their documentation (Mahmood and Vivoni, 2011) were used to obtain terrain, soil, vegetation and meteorological information for model testing. The Triangulated Irregular Network-based Real-time Integrated Basin Simulator (Ivanov *et al.*, 2004) was applied to develop spatiotemporal simulations of the study hillslope (~1280 m^2) located in an open ponderosa pine area of northern New Mexico. Fine-resolution simulations were conducted for three summers (May–September, 1996–1998) encompassing average and wetter-than-average precipitation during the NAM. The following three key field datasets permitted the spatial simulations to be conducted: (1) 14 soil moisture sampling locations over different depth intervals (~4 m in horizontal separation); (2) an aerial survey using Light Detection and Ranging that provided a terrain model and canopy height distributions at ~0.3-m resolution; and (3) an instrumented trench providing runoff estimates (Figure 1).

The spatial model predictions of surface and root zone soil moisture were tested through comparisons with data during separate calibration and validation periods, finding good agreement at grassland and ponderosa pine sites. Simulated runoff rates were also compared with observations and field interpretations as an independent model test. Furthermore, geochemical evidence from Newman *et al.* (1998) was used to support assumptions related to soil and transpiration conditions. After building confidence in the model simulations, the study explored how the fine-resolution interactions within the domain led to emergent patterns in the hillslope hydrologic response (Mahmood and Vivoni, 2011). For example, two distinct soil moisture patterns occur during (a) average and (b) wetter-than-average seasons (Figure 1). Average conditions resemble the vegetation pattern with drier ponderosa pine patches and wetter grassland areas. In contrast, the wetter-than-average period reflected a combination of pine patches and terrain curvature in the soil moisture pattern, a surprising finding for a semiarid hillslope.

What were the underlying physical reasons for the observed switch in the soil moisture pattern? To address this, the subsurface dynamics and evapotranspiration at sampling sites and in the model domain were tracked, finding that the switch was prompted by short periods of lateral moisture redistribution among model elements (Mahmood and Vivoni, 2011). Under frequent rainfall with high cloudiness (Figure 1b), hillslope wetness increased sufficiently to trigger downslope transport that imparted a terrain signature on the surface soil moisture pattern. Under drier conditions (Figure 1a), differences in evapotranspiration among pine patches and grasslands lead to variations in the spatial pattern in soil moisture. As a result, the switching in soil moisture pattern is an expression of the underlying process transformation between vertically dominant (evapotranspiration) and laterally dominant (subsurface transport) fluxes that depend on wetness condition. Thus, the distributed model, supported by comparisons with field data, revealed the existence of two distinct spatial modes of soil moisture variation controlled by biotic (vegetation) and abiotic (terrain) properties. Model-based inferences are now useful in the design of hillslope sensor networks, in the scaling of ecohydrological patterns using plant distributions and in the assessment of forest ecosystem sensitivity to land cover manipulations and climate change.

Watershed soil moisture patterns and evapotranspiration partitioning

An incremental and interactive process was used to characterize the spatial patterns of soil moisture and evapotranspiration during the NAM within a large, mountain basin (~92 km^2) in northern Sonora, Mexico (Vivoni *et al.*, 2007b, 2008b, 2010a). Given the complex terrain, a sparse set of 30 sampling sites and three sensor locations were deployed during the Soil Moisture Experiment in 2004 campaign. These were complemented by a series of airborne flights with two instrument packages for surface soil moisture retrievals (Bindlish *et al.*, 2008; Ryu *et al.*, 2010). Analyses of the ground and remotely sensed soil moisture datasets revealed how wet days exhibited a signature of the mountain elevation gradient, whereas drier days had homogenous soil moisture in the landscape (Vivoni *et al.*, 2007b). This key spatial outcome sets the stage for applying the Triangulated Irregular Network-based Real-time Integrated Basin Simulator model in the study basin using coarse (~30-m resolution) topographic, soil, land cover and meteorological information. The spatial behaviour also corresponded with the following ecosystem variations: (1) lower elevations with subtropical scrublands (SS); and (2) higher areas composed

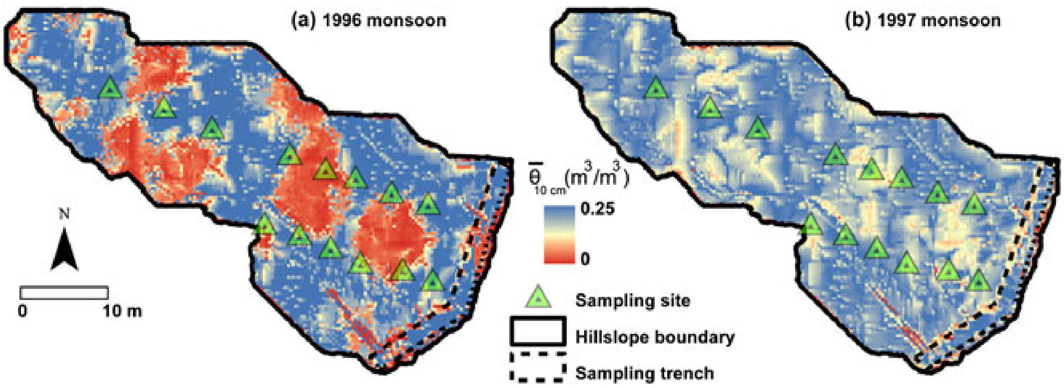

Figure 1. Spatial organization of surface soil moisture at the hillslope scale under (a) vertically dominant and (b) laterally dominant conditions. $\bar{\theta}_{10cm}$ (m^3/m^3) is the time-averaged volumetric soil moisture in the top 10 cm over the North American monsoon period of 15 July–30 September for (a)1996 and (b) 1997. Adapted from Mahmood and Vivoni (2011).

of oak savannas (OS) sampled by two eddy covariance towers (Figure 2a) to characterize the water, energy and carbon dynamics during the NAM. Continuous observations from the SS tower in 2004 were critical for the calibration of soil and vegetation parameters applied to similar ecosystems throughout the mountain basin.

The spatial soil moisture predictions were validated with manual samples along an elevation transect, at two continuous stations and for averaged conditions in the study basin using a hypsometric method (Vivoni *et al*., 2010a). Good agreement was found in capturing terrain controls during wet periods and in representing homogenous dry conditions. Given the consistent model performance relative to distributed data, the spatial organization of soil moisture and evapotranspiration were studied (Vivoni *et al*., 2010a), identifying hysteresis in the relationships between coarse basin-averaged states and the spatial variability in the watershed. These emergent properties were related to the spatial aggregation of fine-scale dynamics, including responses to variable rainfall events and the drying characteristics controlled by soil, terrain and vegetation properties. Thus, the modelling exercise yielded new insight into the spatial organization of ecohydrological systems in the form of an emergent relation that can be tested in other arid and semiarid areas across multiple scales.

These cross-scale interactions were obtained under full-canopy cover during the NAM. Nevertheless, mountain ecosystems differentially green in response to NAM rainfall and species-specific phenology (e.g. Méndez-Barroso *et al*., 2009; Forzieri *et al*., 2011). This assumption can be relaxed by using satellite-based vegetation fields from the Moderate Resolution Imaging Spectroradiometer. For example, the impact of time-variable vegetation states (i.e. plant cover, albedo and leaf area index) on the soil moisture and evapotranspiration simulations was tested in the study basin (Vivoni, 2012). Vegetation greening of SS and OS ecosystems leads to different patterns of evapotranspiration (*ET*) partitioning. In the early NAM period (Figure 2b), lower elevation SS areas green vigorously and increase the fraction of vegetation-mediated losses, $(T+I)/ET$ where T is transpiration and I is canopy evaporation, throughout the basin. As the NAM nears its end (Figure 2c), high elevation OS areas green up and increase $(T+I)/ET$ in a limited area. As a result, the vegetation contribution to basin water losses depends strongly on the spatiotemporal green-up pattern induced by the rainfall distribution and ecosystem water use strategies. Model-based predictions of evapotranspiration partitioning can now be used to guide field studies using manual or automated partitioning techniques (e.g. Yépez *et al*., 2007; Moran *et al*., 2009) that span the seasonal vegetation evolution and sample across different ecosystems.

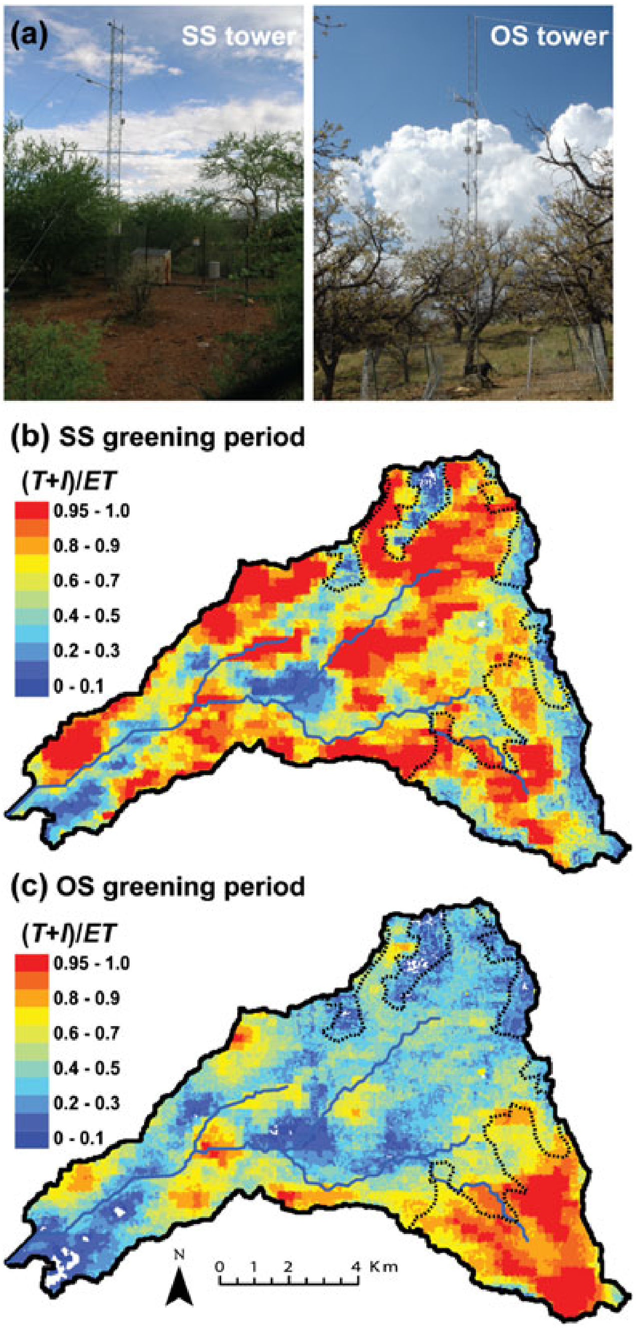

Figure 2. Spatial organization of vegetation-mediated evapotranspiration losses at the watershed scale under (b) subtropical scrubland and (c) oak savanna greening. Two eddy covariance towers in each ecosystem are shown in (a). $(T+I)/ET$ is the hourly ratio of transpiration (T) and canopy evaporation (I) to total evapotranspiration (ET). (b) and (c) are hourly results on 28 July 2004 (12:00 pm) and 10 September 2004 (12:00 pm), respectively. Dashed lines represent the division between lower elevation subtropical scrubland (SS) and higher elevation oak savanna (OS) ecosystems. Adapted from Vivoni (2012).

Woody plant encroachment and ecohydrological patterns in desert catchments

Prior efforts revealed the importance of collocating observations and modelling in the study of spatial ecohydrological patterns. Templeton *et al*. (2010) and Pierini *et al*. (2011) are pursuing a new generation of integrated experiments in small catchments with a legacy of woody plant encroachment or desertification. In the former case, a Chihuahuan desert catchment (~5 ha) in the Jornada Experimental Range (New Mexico) has undergone transitions from a desert grassland to a mixed shrubland over the past 150 years (Gibbens *et al*., 2005). The latter study is in a Sonoran desert catchment (~1 ha) in the Santa Rita Experimental Range (Arizona) where shrub encroachment has lead to a savanna ecosystem

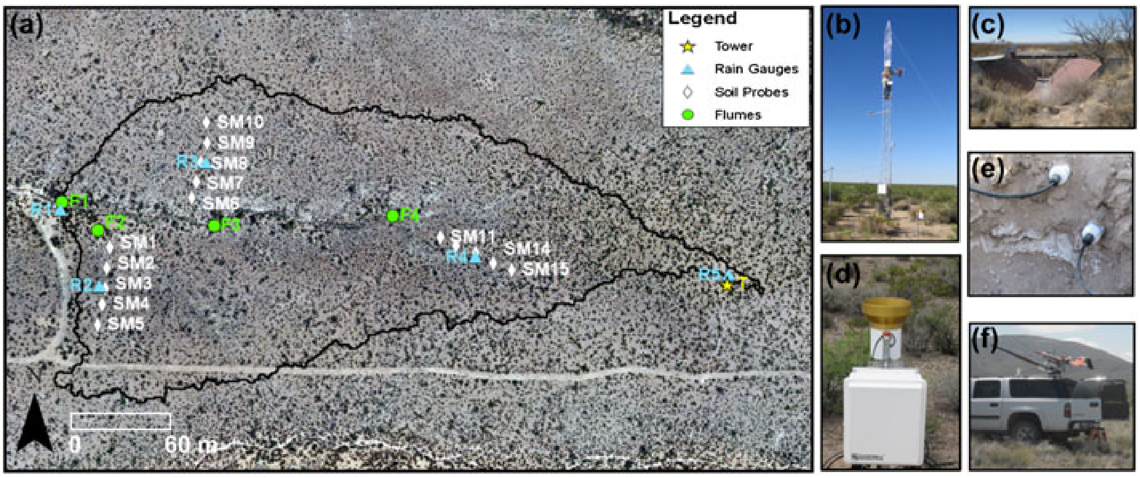

Figure 3. (a) Spatial distribution of a dense sensor network and high-resolution imagery from (f) an unmanned aerial vehicle in a shrubland watershed. Instruments in the sensor network include (b) an eddy covariance tower, (c) four channel flumes, (d) five rain gauges and (e) 48 soil moisture and temperature sensors organized along three transects. Adapted from Templeton (2011).

(Browning *et al.*, 2008). Because the sites have long-term observations and manipulative experiments (Moran *et al.*, 2008), they provide a foundation for spatially explicit sensing and modelling activities oriented towards understanding the role of woody plant encroachment in ecohydrological patterns. Cross-site comparisons may also reveal how differences in climate forcing and species composition affect emergent patterns in the ecosystem biomass, productivity, evapotranspiration and soil moisture, among others.

To illustrate these integrated spatial efforts, a sensor network was established at the Chihuahuan desert site (Figure 3). The first stage of the incremental and iterative process involved the deployment of an eddy covariance tower, a network of rain gauges and runoff flumes and a set of three hillslope transects with soil moisture and temperature sensors. In addition, a sequence of UAV flights (Laliberte *et al.*, 2010) during different phenological stages has been used to derive image mosaics at 6-cm resolution (Laliberte and Rango, 2011) and a 1-m digital elevation model. UAV image analyses provided novel insights on the distributions of the following: (1) terrain properties such as aspect and slope; (2) individual species and canopy heights; and (3) hydrologic characteristics including the boundary shown in Figure 3a. Field sampling of soil and vegetation conditions has also been complemented by a phenological study of representative shrub and grass species in the footprint of the eddy covariance tower (Browning *et al.*, 2011). In the tower footprint, the following two novel experiments are underway: (1) a distributed, continuous network of soil moisture and temperature sensors (as in Vivoni *et al.*, 2010c); and (2) the application of evapotranspiration partitioning (Moran *et al.*, 2009) based on the spatial data. A commensurate experimental design and image acquisition have also been employed at the Sonoran desert site.

Initial analyses from the two experiments indicate that spatial differences in soil moisture in the catchments are important. At the Chihuahuan desert site, Templeton (2011) found that using the distributed soil moisture storage improved the estimation of evapotranspiration as a residual of the watershed water balance, supporting the hypothesis of Scott (2010) on the limitations of point-scale estimates in watershed contexts. These spatial observations will serve as a foundation for a range of model applications that utilize the high-resolution terrain and vegetation data to study the spatial organization of ecohydrological properties. Of particular interest are the spatial linkages between vegetation and soil moisture distributions resolved at the plant to patch scales and the role of species-specific phenological traits. What spatial patterns emerge from fine-scale interactions and how do these help explain woody plant encroachment? Do differences between species phenology influence spatial mixtures of grasses, shrubs and trees at local and downstream locations? Model simulations, tested against spatial field data, will allow evaluating how plant biophysical and phenological properties influence species competition during the process of desertification and in response to climate variability.

CONCLUSIONS

Because the boundaries of ecohydrology are continually expanding, there is an imperative to augment an ecohydrologist's toolbox through the fusion of science and engineering. Existing and novel techniques in sampling, sensing and modelling need to be applied in a coordinated fashion at ecohydrologically relevant locations to improve process understanding and reveal general outcomes. To this end, environmental observatories, such as the National Ecological Observatory Network (e.g. Kampe *et al.*, 2010) and the Critical Zone Observatories (e.g. Anderson *et al.*, 2008), provide an excellent opportunity for re-engaging experimentalists and modellers that should be embraced by the ecohydrological research community. For example, airborne Light Detection and Ranging, imaging spectroradiometer and digital camera observations planned for National Ecological Observatory Network sites (Kampe *et al.*, 2010) can be used to characterize topography, classify vegetation types, structure and biomass and retrieve surface reflectance properties. As illustrated in the case studies, these high-resolution datasets would allow detailed numerical experiments by providing boundary conditions and model parameters, in addition to potentially yielding a set of validation fields to test the spatial predictions. Additional efforts to map surface thermal and moisture properties at high resolution would be desirable, possibly on board manned aircraft or UAV platforms.

The spatial nature of ecohydrology presents a formidable challenge to theory, observations and predictions, in particular, for arid and semiarid regions where the strong coupling of water and ecosystems leads to significant spatiotemporal heterogeneities. As a result, the ecohydrological research community should employ an incremental and iterative process that couples spatial observations from ground and remote sensing platforms with experiments using distributed ecohydrological modelling. The high degree of sophistication of the current generation of numerical models (e.g. Ivanov *et al.*, 2008b; Hwang *et al.*, 2009) is promising, but their applications have been limited to date. As illustrated in the case studies, the modelling exercises afford the opportunity to consolidate the spatial observations in a single framework, test the model performance relative to ground and remote sensing data and explore the cross-scale interactions that underlie the emergent patterns. Models are also excellent tools to generate spatial hypotheses that can be tested in subsequent field studies. Progress towards a geospatial ecohydrology that embraces cross-scale interactions has the potential to yield improved process understanding, predictive capabilities and solutions to current and unanticipated societal challenges related to land and water management in natural and human-dominated systems.

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