

Ecohydrology Bearings—Invited Commentary

Ecohydrology in a human-dominated landscape

Robert B. Jackson,^{1*} Esteban G. Jobbágy² and Marcelo D. Nosoetto²

¹ Department of Biology, Nicholas School of the Environment, and Center on Global Change, Duke University, Durham, NC 27708-0338, USA

² Grupo de Estudios Ambientales - IMASL Universidad Nacional de San Luis/CONICET, San Luis, 5700, Argentina

ABSTRACT

As the earth becomes a quilt of managed patches, ecohydrologists need to move from describing to predicting the consequences of human activities, using knowledge to improve human well-being. We highlight three current opportunities in ecohydrology. The first is the need for stronger research in arid and semi-arid ecosystems, where water is scarce and a tight coupling exists between hydrology and ecology. The second is to build better predictive frameworks for understanding the consequences of vegetation change. The new framework we propose here combines landscape connectivity, through recharge and discharge dynamics, with global climate. In systems where annual precipitation and evapotranspiration are similar, the evapotranspirative differences of altered vegetation can quickly tip the water balance between positive and negative, fundamentally altering water flows and biogeochemistry. The third opportunity is to use simplified agricultural systems to build and test ecohydrological theory. Such systems function under the same biophysical rules but are often better controlled and replicated than more natural ecosystems. Resolving today's controversies requires sound ecohydrological science in a world where the influences of people are increasingly universal. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS ecohydrology; climate change; crop yields; groundwater dynamics; plant transpiration; salinity; vegetation change; water uptake

Received 23 June 2009; Accepted 24 June 2009

INTRODUCTION

Like water itself, the field of ecohydrology is both old and new. The view of ecohydrology as a 'new' scientific discipline might surprise early researchers such as Arnold Engler, who a century ago established paired catchment experiments at the Swiss Federal Research Institute to evaluate the link between hydrology and forest cover. He showed, for instance, that the heavily forested Sperbelgraben catchment produced less runoff during storms than the Rappengraben catchment with only one-third tree cover (Engler, 1919). The novelty of ecohydrology might also surprise Charles Hursch of the Coweeta Hydrologic Laboratory—if he were alive today. In the 1930s, Hursch already understood the importance of transpiration, canopy interception, groundwater links, and many other topics relevant to current ecohydrologists (e.g. Hursch and Brater, 1941).

Despite such history, ecohydrology is an exciting field today because new theories and tools are being applied to its challenges. Recent theoretical developments recognize the importance of stochastic processes and probabilistic representations that couple climate, hydrology and biology. Newer tools such as laser spectroscopy for

determining the ratios of hydrogen, oxygen, and carbon isotopes in the field, geoelectric profiling for estimating soil moisture and salinity, and hyperspectral analyses of plant and surface-soil attributes are revolutionizing the scales and precision of ecohydrological measurements. Students new to the field can find excellent discussions and detailed summaries by authors such as Rodriguez-Iturbe (2000); Eagleson (2002); Eamus *et al.* (2006), and Newman *et al.* (2006).

Ecohydrology is also timely because of the increased pressure on water resources and hydrologic regulation that humans are placing on lands and the environment. Over the last three centuries, the amounts of cropland and pasture globally have increased six-fold to ~1500 and ~3500 million ha, respectively (Goldewijk, 2001). Temperate forests around the world are recovering from past deforestation, while tropical forests are being cut at an alarming rate (e.g. Houghton, 1994; Foley *et al.*, 2005). Plantation forestry is also expanding, with afforestation—planting trees where they were absent for at least 50 years—now comprising approximately 140 million ha alone (FAO, 2006). The earth increasingly resembles a quilt of managed patches.

Climate change, a growing human population, and other factors are increasing demands on the world's water resources and on the lands that help supply them (Jackson *et al.*, 2001). Ecohydrologists should move from description to prediction to help improve water yield and

*Correspondence to: Robert B. Jackson, Department of Biology, Nicholas School of the Environment, and Center on Global Change, Duke University, Durham, NC 27708-0338, USA.
E-mail: jackson@duke.edu

quality across landscapes and to forecast what some of the consequences of deforestation, afforestation, woody encroachment, and other land transformations will be (e.g. Zalewski, 2000; Röckstrom and Gordon, 2001).

The goal of this paper is to highlight some of the places and systems where human manipulation of ecohydrological variables—both biological and physical—are likely to create the greatest opportunities and problems in water yield and quality. That goal includes spatial prediction—how to apply what we learn at one place to make testable predictions elsewhere—as well as temporal prediction—how we can forecast outcomes with more confidence, recognizing that the world is a stochastic place.

We begin by providing a brief overview of how vegetation change affects water yield, highlighting systems with the largest uncertainties. We then discuss a framework for predicting where vegetation shifts have large biogeochemical consequences based on the balance of precipitation and evapotranspiration and switches between recharge and discharge zones. Finally, we discuss how agricultural and other managed ecosystems provide an untapped resource for ecohydrologists, particularly when multiple plant types can be compared directly. Overall, we hope to spur hydrologic research by highlighting some key unanswered questions.

LOW FLOW AND NO FLOW: INTERACTIONS IN WATER-LIMITED ECOSYSTEMS

Since the pioneering work of Arnold Engler, many researchers have examined the relationship between the type and cover of vegetation on water yield and quality (e.g. Bosch and Hewlett, 1982; Holmes and Sinclair, 1986; Vertessy, 1999; Jackson *et al.*, 2005). In general, transpiration, interception, and evaporation increase at the expense of water yield when grasslands or shrublands are replaced with forests, at least in relatively mesic systems. Climate variation interacts with land use to influence the extent of changes in the water balance, as well. As the tree density and leaf-area increase, the water balance shifts towards greater evapotranspiration and stemflow, but variation in the amount and timing of precipitation also influences the differences observed, including how much of the water evaporates from the soil or is transpired by plants (e.g. Zou *et al.*, 2008).

Farley *et al.* (2005) highlighted the contrast between absolute and relative changes in runoff with afforestation along a precipitation gradient, one important component of climate. On the basis of a comprehensive analysis of catchment data, they concluded that replacing grasses or shrubs with trees caused the greatest average losses in absolute stream flow of ~ 290 mm at wetter sites [>1500 mm mean annual precipitation (MAP)]. In contrast, the largest relative losses, almost two-thirds of original stream flow, were found on average at drier sites (<1000 mm MAP). In fact, streams dried up completely with afforestation in approximately one of every eight

cases in the analysis, all of which occurred at sites receiving $<\sim 1250$ mm MAP a year (Jackson *et al.*, 2005). Relative losses in stream flow increased linearly with increasing aridity.

One important unresolved question is the level of annual precipitation at which the above linear relationship breaks down (and the hydrologic factors that influence this outcome). The driest site in the catchment database of Farley *et al.* (2005) was 880 mm MAP. Zhang *et al.* (2001) suggest that large relative differences between grasses and woody plants are maintained in systems from approximately 800 mm down to 350 mm MAP, but the differences shrink as precipitation approaches the lower value. Below this value, differences in evapotranspiration (ET) typically disappear because $ET \approx MAP$ for any plant cover. The precipitation level at which plant cover no longer affects water yield depends upon the ecohydrological context, including biological variables, such as leaf area, rooting depth, and phenology (i.e. seasonality of plant activity), climatic variables including the seasonality and intensity of precipitation and temperature constraints on plant growth, and landscape configuration variables such as slope, rockiness, soil texture, and groundwater depth and abundance (Huxman *et al.*, 2005; D'Odorico and Porporato, 2006; Newman *et al.*, 2006). Given the importance of water in semi-arid systems, future research should quantify the ecohydrological controls on water use there, especially in the framework of woody encroachment and plantations for carbon sequestration.

Altered low flow is another critical hydrologic change that arises with shifts in vegetation. In fact for aquatic species, low flow can be more important than annual stream flow, especially during warmer or drier conditions when groundwater influx through the hyporheic zone helps organisms survive (e.g. Findlay, 1995; Poff *et al.*, 1997; Smakhtin, 2001). Compared to native grasslands and shrublands, catchment data clearly show that trees reduce low flow substantially (e.g. Riggs, 1985; Scott and Smith, 1997). Across the data set of Farley *et al.* (2005), relative losses in low flow with afforestation were tightly correlated with, but proportionally larger than, losses in annual flow. Dry-season losses may therefore be even more severe than total annual losses for afforestation or woody encroachment, possibly leading to shifts from perennial to intermittent flow regimes in drier regions. Because of the lack of catchment data for systems with <800 mm MAP, we need additional data and better estimates of hydrologic variables across such ecosystems.

RECHARGE AND DISCHARGE CONNECTIONS: A FRAMEWORK FOR ECOHYDROLOGICAL PREDICTIONS

A key part of understanding the ecohydrological effects of human actions is landscape connectivity. Ecohydrological connections occur below ground, through the lateral flow of ground water, and aboveground, through overland flow. While below-ground connections tend to be

slow and persistent, aboveground connections are typically more sporadic and rapid (e.g. Okin *et al.*, 2009). Across the globe, humans dramatically affect landscape connectivity and, hence, the movement of water, soil, nutrients, and pollutants.

Climate and land-use influence surface connectivity together. For instance, in flat, sedimentary regions such as the South American Pampas, the lowest landscape positions hold small water bodies that are poorly connected by groundwater flow. After unusually wet periods, often across years, ground water rises gradually and the water bodies coalesce, increasing regional water cover from 3 to 30% and triggering large-scale overland flow. Groundwater rise may be linked not just to rainfall but also to the expansion of agriculture across the region, as suggested by historical data of water-table levels (Viglizzo *et al.*, 2009). Shallower-rooted crops stop using groundwater before deeper-rooted native species do and are less tolerant of waterlogging, leading to higher groundwater levels that facilitate flooding (Viglizzo *et al.*, 2009).

One framework for predicting the consequences of connectivity and vegetation change is the balance of recharge and discharge across landscapes. In upland systems, ecohydrological connections typically occur primarily through recharge, driving a one-way flow of water and solutes downwards from ecosystems to aquifers (e.g. Freeze and Cherry, 1979; George *et al.*, 1999). The opposite phenomenon, discharge, or groundwater flow towards the surface, is typically localized to a small proportion of the landscape occupied by low-lying riparian zones and wetlands. When ground water in discharge zones evaporates, it leaves behind the salts the water contained, potentially increasing salinity.

Although recharge and discharge zones are typically viewed as topographically fixed across landscapes, shifts in vegetation and hydrology can overcome topographic controls and alter recharge and discharge zones. For

example, changes in recharge rates or groundwater consumption can reshape hydraulic gradients, altering solute fluxes and water movement vertically and horizontally across landscapes (e.g. Heuperman, 1999). Probably the best known example is the salinization and groundwater rise afflicting southern Australia after crops and pastures replaced native woodlands. This change triggered the onset of recharge and solute transport after millennia in which those processes were missing (e.g. Schofield, 1992). Flat, humid grasslands are another case where such processes are important, including the Pampas of Argentina, the Carpathian basin in central Europe, and the Great Plains of western Canada.

A first step in predicting which systems may be most vulnerable to human-induced shifts in recharge and discharge is to identify locations around the world where annual precipitation and evapotranspiration are similar ($\pm 15\%$, for instance) (Figure 1). These regions are where the evapotranspirative differences of contrasting vegetation are most likely to tip the water balance from positive to negative (or vice versa). For instance, if ET is close to but smaller than MAP for one vegetation type, an increase in ET with vegetation change will interrupt recharge and initiate discharge if water is available from lateral flow or ground water. Humid grasslands, where $ET < P$ by 10 or 20% is one such case. The establishment of trees can reverse the sign of this relationship, initiating a net discharge regime ($ET > P$) where groundwater uptake exceeds deep drainage (net discharge).

This possibility is precisely what we observed for eucalypt and pine plantations in the humid grasslands of Argentina (see map in Figure 1), where relatively shallow ground water provides an additional source of water for trees. According to the results from three separate approaches—sap flow measurements, a chloride balance, and groundwater modelling—eucalypt plantations there transpired 250 to 500 mm of additional water compared with the native grasslands or croplands around them,

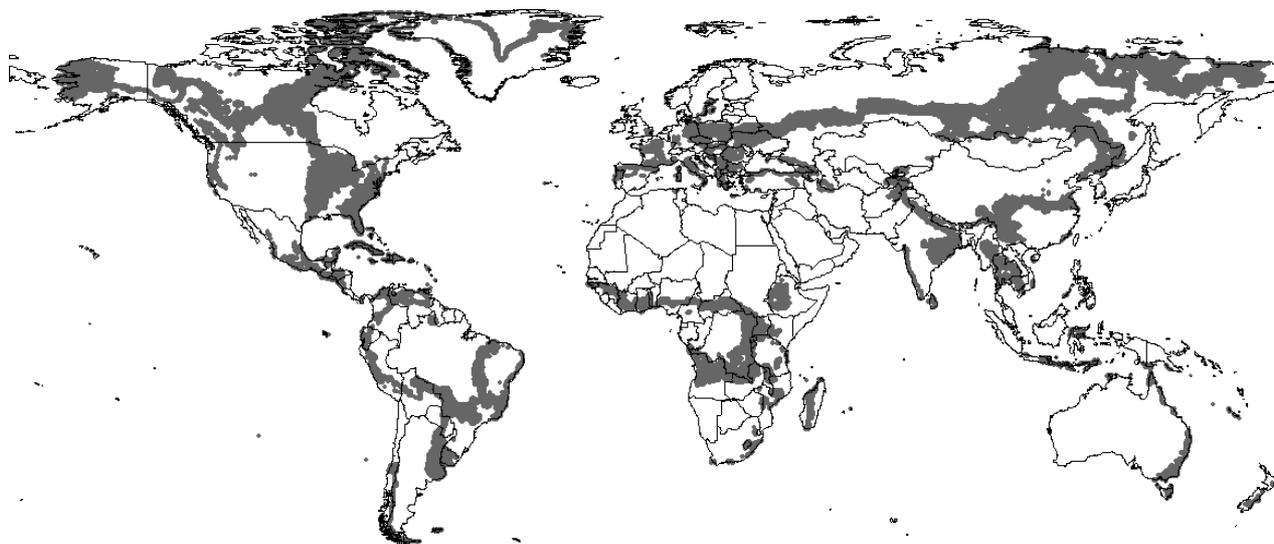


Figure 1. A global map of locations where the ratio of P/ET (mean annual precipitation divided by Penman-Monteith potential evapotranspiration) lies between 0.85 and 1.15. The climatic data used in the calculations are from the CRU CL 2.0 database (1961–1990) from the UK Climate Research Unit, with a spatial resolution of 10 min (New *et al.*, 2002).

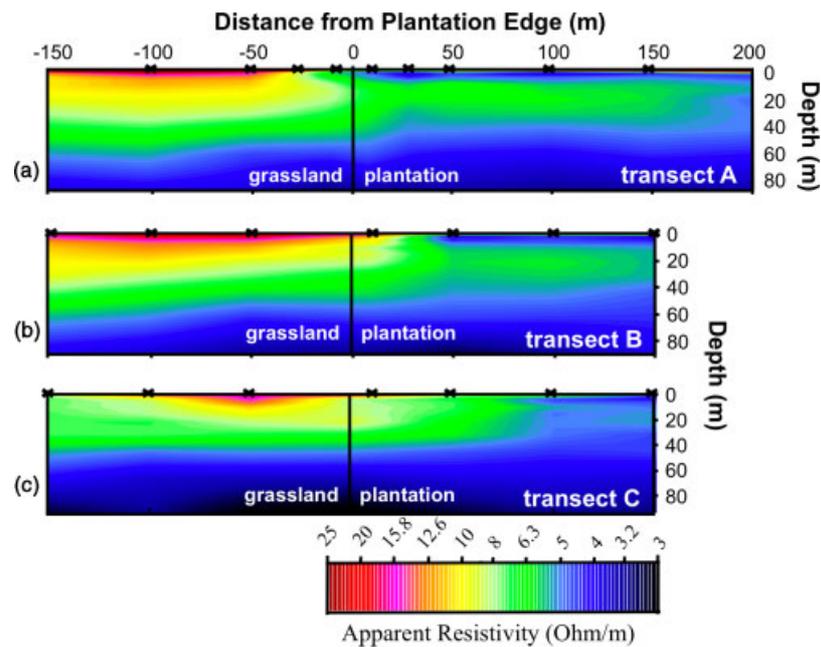


Figure 2. Effects of plantations on groundwater salinity and electrical conductivity in the Argentine Pampas based on measurements of geoelectric profiling. Three transects across plantation/grassland borders at Castelli, Argentina were made using vertical electric soundings, with red colour indicating fresher water (higher resistivity) and blue colour indicating saltier water (lower resistivity). Reproduced from Jackson *et al.* (2005).

inducing localized discharge regimes across the landscape (Engel *et al.*, 2005; Jobbágy and Jackson, 2007; Nosetto *et al.*, 2008).

Shifts between local recharge and discharge zones alter not just the water balance but the salinity balance as well, as salts move into the local discharge zone by mass flow. Groundwater salinity under the eucalypt plantations in humid Argentina was 15 to 30 times saltier—one fourth the salinity of sea water—than under adjacent grasslands only 100 m away (Figure 2; Jackson *et al.*, 2005). Electrical conductivity and Cl^- concentrations in the plantation soils were an order of magnitude greater down to 5 m, and soils even turned sodic in some cases, with exchangeable sodium percentages $>15\%$ (Jobbágy and Jackson, 2004, 2007). These whole-scale transformations in soil and groundwater chemistry raise profound questions about the sustainability of plantations in some regions and arise solely from the ecohydrological changes induced by vegetation change.

Some salinization may be unavoidable where afforestation leads to net groundwater discharge if no mechanism exists to remove accumulated solutes. In the Argentine Pampas, soil salinity patterns across a regional climatic gradient of afforested grasslands suggested that trees were able to switch the water balance from positive to negative only where MAP was $<1100 \text{ mm year}^{-1}$, triggering salinization in these locations alone (Nosetto *et al.*, 2008). The intensity of salinization also varied predictably with the salinity tolerances of the tree species planted.

The salinization pattern observed in the Pampas is mirrored in the Great Hungarian Plains (MAP = 540 mm year^{-1}), where oak plantations in native grasslands led to intense groundwater discharge ($\sim 350 \text{ mm year}^{-1}$) and soil and groundwater salinization (Nosetto *et al.*, 2007).

Tree establishment has also led to soil and groundwater salinization in grass-steppes in Russia and in Pakistan (Khanzada *et al.*, 1998; Sapanov, 2000; Mahmood *et al.*, 2001), with recharge interruption and groundwater use by trees proposed as causes. In addition to grassland afforestation, any land-use change able to generate a net groundwater discharge has the potential to lead to long-term solute accumulation.

AGRICULTURAL SYSTEMS: SIMPLIFYING THE 'ECO' IN ECOHYDROLOGY

Besides the intrinsic importance of agriculture and the challenges of production and sustainability, agricultural systems provide unique opportunities to study ecohydrological processes in a more controlled and replicated manner than in most natural systems (e.g. Famiglietti *et al.*, 1999; Callow and Smettem, 2009). Croplands also illustrate many of the same effects of local discharge and recharge and altered biogeochemistry described above.

Potential shifts between discharge and recharge zones can occur when native vegetation is replaced with agriculture. Scanlon *et al.* (2005) compared native rangeland ecosystems with dryland and irrigated croplands at sites in the Amargosa Desert of Nevada and in the Texas high plains. They found that recharge under native arid and semi-arid rangelands was negligible, with a slight estimated upward movement of water ($<0.1 \text{ mm year}^{-1}$). Not surprisingly, the irrigated croplands ($\sim 450 \text{ mm}$ of added water year^{-1} from $\sim 40 \text{ m}$ underground) switched to local recharge zones (downward flux of $\sim 130\text{--}640 \text{ mm year}^{-1}$), with rising groundwater levels and downward flux of chloride and nitrate. Even the reduced transpiration of the dryland agriculture was

sufficient to switch the native regime from discharge to recharge, with an estimated net downward flow of $\sim 9\text{--}32\text{ mm year}^{-1}$ and detectable increases in groundwater depth and solute load.

In addition to improved replication and control in many agricultural systems, agricultural technologies offer another advantage for ecohydrologists. Precision agriculture uses data from global positioning systems (GPS) to optimize fertilizer use and other treatments at scales of meters or less (e.g. Stafford, 2000). High-precision harvests provide similar data for aboveground primary productivity and yield, measurements that are more variable and challenging in less managed ecosystems.

We examined the reciprocal coupling between vegetation, climate, and groundwater depth in agricultural fields of South America that had shallow water tables characteristic of the region (0–10 m depth). In such situations, ground water may help (water provision), harm (water logging), or have no influence on plant productivity. Understanding how climate and vegetation type influence this relationship requires ecological data, such as leaf-area, rooting depth, and phenology, and hydrological data, such as the rainfall variation across years and the controls on lateral flow. We combined high-resolution data on corn, soybean, and wheat yields with topographic maps and groundwater-depth sampling of 18 monitoring wells and nine boreholes to identify the groundwater depths that optimized crop yields across years.

Through two growing seasons, the optimum groundwater depth ranges were 1.4–2.5 m for corn, 1.2–2.2 m for soybean and only 0.7–1.6 m for the shallower-rooted, winter-season wheat plants (Nosetto *et al.*, 2009). Shallower water-table levels were associated with sharply dropping yields (0.05 kg m^{-2} for every 10-cm increase in groundwater depth), most likely as a consequence of waterlogging and salinity; deeper water table levels were accompanied by steady declines in yield until ground water was no longer accessible to the plants (Figure 3). Similar to grassland afforestation, direct groundwater use by crops also increased groundwater salinity up to levels that sometimes hindered further uptake and reduced growth.

Inter-annual differences in how groundwater depth affected crop yields can be explained largely by differences in precipitation (Nosetto *et al.*, 2009). Rainfall during the first growing season was 27% higher than average, 685 mm, while in the second growing season it was only 421 mm, 22% below average. The drier year revealed a much tighter sensitivity and coupling of yield to groundwater depth than the wetter year did ($r^2 = 0.75$ vs $r^2 = 0.48$; Figure 3).

CONCLUSIONS

Ecohydrology provides a predictive framework for managing water in today’s human-dominated world. The current revolution in ecohydrology is founded on the reciprocal feedback between biology and hydrology. A greater

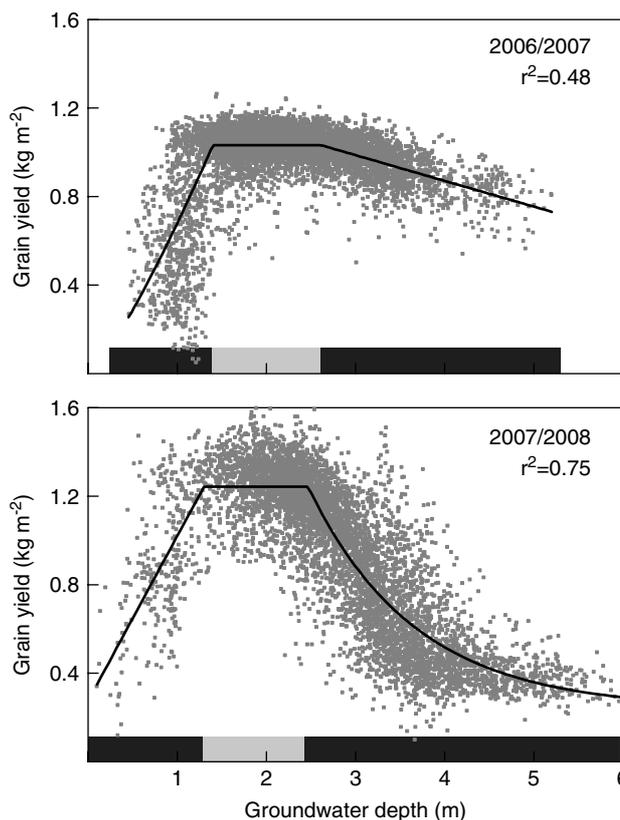


Figure 3. Relationships of corn yields (kg m^{-2}) and groundwater depth (m) in the inland Pampas of Argentina for the relatively wet 2006–2007 (upper panel) and dry 2007–2008 (lower panel) growing seasons. From Nosetto *et al.* (2009).

appreciation of biology results in a more complete hydrological description. A broader hydrological context, in turn, creates testable theory in biology. Quantifying the importance of the ‘eco’ in ecohydrology makes prediction and mechanistic understanding increasingly possible.

In this paper we emphasize three opportunities. The first is to work in systems where there is a tight coupling of hydrological partitioning and ecological dynamics. This coupling is evident and especially poorly understood in the world’s arid and semi-arid ecosystems. The second opportunity is the need to build better predictive frameworks for the consequences of ecohydrological change. The framework we proposed combines landscape connectivity, through recharge and discharge dynamics, with global predictions of systems where annual precipitation and evapotranspiration are similar (Figure 1). In these regions, the evapotranspirative differences of altered vegetation can quickly tip the water balance from positive to negative or negative to positive. The third opportunity is to use simplified agricultural systems to build and test ecohydrological theory. Such systems function under the same biophysical rules but are often more tightly controlled and better replicated than more natural ecosystems.

Overall, biophysical and hydrological frameworks can help researchers predict where certain ecohydrological attributes will be found and where particular changes may be the greatest (e.g. Schenk and Jackson, 2005).

Plant characteristics can help scientists predict how water supply and quality will differ with vegetation change. In South Africa, for instance, invasive alien plants are estimated to have reduced river flows by about 7% (Le Maitre *et al.*, 2002). The Working for Water programme that pays to control invasives there is predicated on sound ecohydrological knowledge of plant type and water yield. Across the globe in the Owens Valley of California, the Los Angeles Department of Water and Power (LADWP) has pumped between 50 000 and 200 000 acre-feet of ground water into the Los Angeles aqueduct each year since 1970. How much ground water is pumped depends on an agreement to maintain adequate plant cover and to avoid shifts in vegetation type, such as from grassland/meadow vegetation to scrub communities. What constitutes 'significant decreases' in ecosystem health is a point of contention worth millions of dollars each year (e.g. Elmore *et al.*, 2003).

Resolving these kinds of controversies requires sound ecohydrological science in a world where human influences are increasingly universal. That challenge and opportunity is the core of ecohydrology today.

ACKNOWLEDGEMENTS

We thank the Jackson lab, Dave Breshears, and an anonymous reviewer for helpful comments on the manuscript. This research was supported by the National Science Foundation (DEB-0717191) and the Inter-American Institute for Global Change Research (IAI, CRNII 2031, supported by the NSF, GEO-0452325).

REFERENCES

- Bosch JH, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes and water yield and evapotranspiration. *Journal of Hydrology* **55**: 3–23.
- Callow JN, Smettem KRJ. 2009. The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes. *Environmental Modelling & Software* **24**: 959–968.
- D'Oroico P, Porporato A. 2006. *Dryland Ecohydrology*. Springer: Dordrecht, The Netherlands.
- Eagleson PS. 2002. *Ecohydrology: Darwinian Expression of Vegetation form and Function*. Cambridge University Press: UK.
- Eamus D, Hatton T, Cook C, Colvin C. 2006. *Ecohydrology: Vegetation Function, Water and Resource Management*. CSIRO Publishing: Collingwood.
- Elmore AJ, Mustard JF, Manning SJ. 2003. Regional patterns of plant community response to changes in water: Owens Valley, California. *Ecological Applications* **13**: 443–460.
- Engel V, Jobbágy EG, Stieglitz M, Williams M, Jackson RB. 2005. The hydrological consequences of Eucalyptus afforestation in the Argentine Pampas. *Water Resources Research* **41**: W10409. DOI: 10.1029/2004WR003761.
- Engler A. 1919. Untersuchungen über den Einfluss des Waldes auf den Stand der Gewässer. *Mitteilungen der Schweizerischen Zentralanstalt für das forstliche Versuchswesen* **12**: 1–626.
- Famiglietti JS, Devereaux JA, Laymon CA, Tsegaye T, Houser PR, Jackson TJ, Graham ST, Rodell M, van Oevelen PJ. 1999. Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. *Water Resources Research* **35**: 1839–1851.
- FAO. 2006. *Global Forest Resource Assessment 2005*. United Nations Food and Agriculture Organization: New York City.
- Farley KA, Jobbágy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* **11**: 1565–1576.
- Findlay S. 1995. Importance of surface-subsurface exchange in stream ecosystems: the hyporheic zone. *Limnology and Oceanography* **40**: 159–164.
- Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK. 2005. Global consequences of land use. *Science* **5734**: 570–574.
- Freeze RA, Cherry JA. 1979. *Groundwater*. Prentice-Hall: Upper Saddle River, NJ; 605.
- George RJ, Nulsen RA, Ferdowsian R, Raper GP. 1999. Interactions between trees and groundwaters in recharge and discharge areas—a survey of Western Australian sites. *Agricultural Water Management* **39**: 91–113.
- Goldewijk KK. 2001. Estimating global land use change over the past 300 years: the HYDE database. *Global Biogeochemical Cycles* **15**: 417–433.
- Heuperman A. 1999. Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems. *Agricultural Water Management* **39**: 153–167.
- Holmes JW, Sinclair JA. 1986. Water yield from some afforested catchments in Victoria. *Hydrology and Water Resources Symposium*. River Basin Management, Griffith University, Brisbane, 25–27 November 1986, Institution of Engineers: Australia, Barton, ACT, Australia.
- Houghton RA. 1994. The worldwide extent of land-use change. *Bioscience* **44**: 305–313.
- Hirsch CR, Brater EF. 1941. Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow. *Transactions-American Geophysical Union Part 3* **22**: 863–871.
- Huxman TE, Wilcox BP, Breshears DD, Scott RL, Snyder KA, Small EE, Hultine K, Pockman WT, Jackson RB. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* **86**: 308–319.
- Jackson RB, Carpenter SR, Dahm CN, McKnight DM, Naiman RJ, Postel SL, Running SW. 2001. Water in a changing world. *Ecological Applications* **11**: 1027–1045.
- Jackson RB, Jobbágy EG, Avissar R, Baidya Roy S, Barrett D, Cook CW, Farley KA, Le Maitre DC, McCarl BA, Murray B. 2005. Trading water for carbon with biological carbon sequestration. *Science* **310**: 1944–1947.
- Jobbágy EG, Jackson RB. 2004. Groundwater use and salinization with grassland afforestation. *Global Change Biology* **10**: 1299–1312.
- Jobbágy EG, Jackson RB. 2007. Groundwater and soil chemical changes under phreatophytic tree plantations. *Journal of Geophysical Research—Biogeosciences* **112**: G02013. DOI: 10.1029/2006JG000246.
- Khanzada AN, Morris JD, Ansari R, Slavich PG, Collopy JJ. 1998. Groundwater uptake and sustainability of *Acacia* and *Prosopis* plantations in Southern Pakistan. *Agricultural Water Management* **36**: 121–139.
- Le Maitre DC, van Wilgen BW, Gelderblom CM, Bailey C, Chapman RA, Nel JA. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management* **160**: 143–159.
- Mahmood K, Morris J, Collopy J, Slavich P. 2001. Groundwater uptake and sustainability of farm plantations on saline sites in Punjab province, Pakistan. *Agricultural Water Management* **48**: 1–20.
- New M, Lister D, Hulme M, Makin I. 2002. A high-resolution dataset of surface climate over global land areas. *Climate Research* **21**: 1–25.
- Newman BD, Wilcox BP, Archer SR, Breshears DD, Dahm CN, Duffy CJ, McDowell NG, Phillips FM, Scanlon BR, Vivoni ER. 2006. Ecohydrology of water-limited environments—a scientific vision. *Water Resources Research* **42**: W06302. DOI: 10.1029/2005WR004141.
- Noisetto MD, Jobbágy EG, Tóth T, Di Bella CM. 2007. The effects of tree establishment on water and salts dynamics in naturally salt-affected grasslands. *Oecologia* **152**: 695–705.
- Noisetto MD, Jobbágy EG, Tóth T, Jackson RB. 2008. Patterns and controls of ecosystem salinization with grassland afforestation across a rainfall gradient. *Global Biogeochemical Cycles* **22**: GB2015. DOI: 10.1029/2007GB003000.
- Noisetto MD, Jobbágy EG, Jackson RB, Sznajder GA. 2009. Reciprocal influence between crops and shallow ground water in sandy landscapes of the inland Pampas. *Field Crops Research* **113**: 138–148.
- Okin GS, Parsons AJ, Wainwright J, Herrick JE, Bestelmeyer BT, Peters DC, Fredrickson EL. 2009. Do changes in connectivity explain desertification? *Bioscience* **59**: 237–244.
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for conservation and restoration of river ecosystems. *Bioscience* **47**: 769–784.

- Riggs HC. 1985. *Stream Flow Characteristics*. Elsevier: Amsterdam.
- Rockström J, Gordon L. 2001. Assessment of green water flows to sustain major biomes of the world: implications for future ecohydrological landscape management. *Physics and Chemistry of the Earth* **26**: 843–851.
- Rodriguez-Iturbe I. 2000. Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research* **36**: 3–9.
- Sapanov MK. 2000. Water uptake by trees on different soils in the Northern Caspian region. *Eurasian Soil Science* **33**: 1157–1165.
- Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy K. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* **11**: 1577–1593.
- Schenk HJ, Jackson RB. 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma* **126**: 129–140.
- Schofield NJ. 1992. Tree-planting for dryland salinity control in Australia. *Agroforestry Systems* **20**: 1–23.
- Scott DF, Smith RE. 1997. Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. *Water SA* **23**: 135–140.
- Smakhtin VU. 2001. Low flow hydrology: a review. *Journal of Hydrology* **240**: 147–186.
- Stafford JV. 2000. Implementing precision agriculture in the 21st century. *Journal of Agricultural Engineering Research* **76**: 267–275.
- Vertessy RA. 1999. The impacts of forestry on streamflows: a review. In *Forest Management for Water Quality and Quantity. Proceedings of the Second Forest Erosion Workshop*, Warburton, Australia. Report 99/6, Croke J, Lane P (eds). Cooperative Research Centre for Catchment Hydrology, CSIRO Land and Water: Canberra; 93–109.
- Viglizzo EF, Jobbagy EG, Carreño LV, Frank FC, Aragón R, de Oro L, Salvador VS. 2009. The dynamics of cultivation and floods in arable lands of central Argentina. *Hydrology and Earth System Sciences* **13**: 491–502.
- Zalewski M. 2000. Ecohydrology—the scientific background to use ecosystem properties as management tools toward sustainability of water resources. *Ecological Engineering* **16**: 1–8.
- Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**: 701–708.
- Zou CB, Breshears DD, Newman BD, Wilcox BP, Gard MO, Rich PM. 2008. Soil water dynamics under low-versus high-ponderosa pine tree density: ecohydrological functioning and restoration implications. *Ecohydrology* **1**: 309–315.