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Transformative ecosystem change and ecohydrology: ushering in a new era for watershed management

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ABSTRACT

As a result of human activities, forests and rangelands across the globe have undergone dramatic changes that have fundamentally altered ecosystem processes. Examples of these kinds of transformational changes include increasingly hot and extensive forest fires, die-off over vast areas of forest from insect infestations, large-scale encroachment of rangelands by woody plants and non-native invasive plants, and desertification. These changes have accelerated in pace, scale and magnitude in recent decades and have the potential to alter water, energy, and biogeochemical cycles in important but not fully understood ways. The related disciplines of ecohydrology and watershed management are being shaped and transformed by the need to understand the ecohydrological consequences of transformative landscape change as well as the need to mitigate and manage for these changes.

KEY WORDS woody plant encroachment; degradation; invasive species; forest die-off

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INTRODUCTION

We have entered an era that is increasingly dominated by *transformative change*. As a result of human activities (Steffen *et al.*, 2007; Steffen, 2008), our forests and rangelands are changing at an unprecedented rate (Bonan, 2008; Jackson *et al.*, 2008). Understanding how these changes affect the water cycle is an urgent need and will be a major challenge for ecohydrology and watershed management in the 21st century.

By transformative change, I am referring to profound or radical changes to the earth's surface that fundamentally alter ecosystem processes. Some of these changes are brought about by intentional decisions by society—such as urbanization, agricultural conversion, and afforestation (Foley *et al.*, 2005; Scanlon *et al.*, 2007; Stonestrom *et al.*, 2009). Others—those I wish to emphasize—are unintentional and often unanticipated environmental and land-cover changes. Examples include the increasingly hot and extensive forest crown fires, die-off over vast areas of forest from insect infestations, large-scale encroachment of grasslands by woody and invasive plants, and increasing losses of land to desertification. Although recognized as important for some time, in recent decades these unintentional changes have accelerated in pace, magnitude, and scale (Ryan *et al.*, 2008a). Collectively they have profound implications for water and biogeochemical cycles (Huxman *et al.*, 2005; Campbell *et al.*, 2009), but these implications are not fully understood.

The focus of wildland watershed management has traditionally been to protect and maintain water resources through good land management—mitigating, if you will, the effects of land-cover changes that resulted from *intentional* activities such as forest-harvesting, road-building, grazing, and recreation (Brooks *et al.*, 2003). This management strategy is prescriptive and anticipatory, and is still important; but increasingly, watershed managers are being forced to be reactive—that is, to respond to the unanticipated alteration of ecosystems by unintentional transformative change. This shift in direction is seen globally, and will continue. Examples of such reactive management include South Africa's $100 million-per-year programme to remove invasive species in an effort to save water (Koenig, 2009) and the massive expenditure of resources in the United States for preventing and combating wildfires as well as restoring watersheds after fires (United States Government Accountability Office, 2007).

The other change that has occurred in watershed management is the general acknowledgement that managing landscapes for increased water yield at large scales is simply not practical (and, to be frank, almost never works). A recent review by the National Academy of Sciences (2008) supports this conclusion, stating that under such a management strategy, (1) increases in water yield are small and unsustainable; (2) water quality can be diminished; (3) there is little return during dry periods; and

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(4) the size of the area needing to be treated is prohibitively large.

The gradual recognition of the shortcomings of this strategy, both within and outside the profession, has robbed the watershed management effort of some of the vitality it displayed in the 1960s, 1970s, and early 1980s. And—judging by student numbers and professional opportunities—it is fair to say that the profession has been in decline for some time. I believe that this trend will be reversed because of the urgency of addressing the watershed challenges brought about by transformative landscape change. It is the need to meet these challenges that is redefining and reinvigorating the discipline of watershed management. (The emergence and growing awareness of ecohydrology is evidence that this is already happening.) Further, the tremendous research and development work that went into the effort to manage watersheds for increased water yield will provide a solid foundation for understanding and addressing the effects of transformative change on the water cycle.

TRANSFORMATIVE CHANGE AND THE WATER CYCLE—EXAMPLES ALONG AN ELEVATION GRADIENT

Transformative ecosystem change is occurring everywhere (Hooke, 2000), and a comprehensive review is well beyond the scope of this paper. Instead I will select a few examples, mainly from western North America. These are organized according to a hypothetical elevation gradient, from high to low—which not only highlights the extensive nature of transformative change but also, by facilitating comparisons, may contribute to the effort to (1) understand the ecohydrological consequences and (2) develop effective management strategies. For example, transformative landscape change in higher-elevation landscapes is driven mainly by a changing climate and is more recent than in lower-elevation landscapes, where the principal driver has been changes in land-use activities.

High elevations—a changing snow regime

Transformative ecosystem change is occurring at higher and higher elevations, primarily in response to a warming climate. The changes include accelerated melting of glaciers (Xu *et al.*, 2009), modified snow regimes (Barnett *et al.*, 2008), and a shifting tree line (Butler *et al.*, 2009). Of particular concern, in relation to water supply, is how these changes will affect the timing and amount of streamflow. In the western United States, where a large percentage of the water supply is generated from high-elevation areas, the effects of modified snow hydrology are already being seen. Snow makes up a smaller percentage of precipitation, and spring snowmelt begins earlier—the net result being lower total flows and greatly diminished flow in the summer and fall (Stewart *et al.*, 2005; Stewart, 2009). These changes in streamflow have dramatic implications for water resource management in the western United States and other semi-arid regions where snowmelt is the primary source of streamflow (Milly *et al.*, 2005, 2008).

Midlands—forests under stress

Forests worldwide are under tremendous pressure from over-utilization, climate change, and invasive species (Bonan, 2008). In the western United States, forests are being radically transformed by two related phenomena: increasing wildfires and tree mortality by insect damage (Ryan *et al.*, 2008a).

Although fires are a natural part of these forests, it appears that the types of fires large enough to devastate entire stands of trees are increasing. A warming climate is largely responsible, although past land-management policies have contributed as well (Swetnam *et al.*, 1999; Westerling *et al.*, 2006). The warmer mid-elevation temperatures result in smaller snowpacks and spring and summer conditions that render these forests more susceptible to destructive crown fires. As the climate continues to warm, fires of this kind will only increase in the future (Ryan *et al.*, 2008a). The hydrological response to forest fires is well documented. Both runoff and sediment loads generally increase significantly following fires (Moody *et al.*, 2008; Moody and Martin, 2009).

No example better illustrates how transformative environmental change is forcing management into a more reactive mode. Billions of dollars have been spent in trying to prevent wildfires, combat wildfires, and rehabilitate landscapes following wildfire (Stokstad, 2008). The success of this strategy has been vigorously debated (Wuerthner, 2006).

The second, important example of transformative landscape change in forests has been the large-scale die-off of trees (mostly pine) in western North America, owing to a combination of water stress and insect infestations (Logan *et al.*, 2003; van Mantgem *et al.*, 2009; Allen *et al.*, in press). Insect outbreaks have been facilitated by years of low precipitation and relatively mild winters. Climate variability and, in particular, the extent and frequency of drought have significant and potentially long-lasting effects on the structure and composition of forest stands: killing some species, making trees more susceptible to insect infestation, and increasing the likelihood of fires (Breshears, 2005; Allen, 2007; Ryan *et al.*, 2008b; Breshears *et al.*, 2009). The recent dramatic rise in forest mortality is most certainly related to changes in temperature and precipitation (van Mantgem *et al.*, 2009), and the extent of the affected areas is enormous (Raffa *et al.*, 2008). Some have suggested that most, if not all, of the lodgepole pine forests from Mexico to Canada will eventually succumb.

The magnitude of the current forest mortality phenomenon is unprecedented in recent history and at present, the ecohydrological consequences of these changes are largely unknown. An extrapolation of some early watershed work that examined the effects of timber harvesting on water yield suggests that regional streamflows could increase as a result of forest die-off (Stednick,

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1996). On the other hand, if snow accumulation continues to decline in these mid-elevation forests, the expected increases in streamflow may not materialize.

Low elevations—evolving rangelands

Rangelands are found mainly at lower elevations, at least in the American West. The landscapes at these elevations have been the object of the most long-term and intensive use by humans, and human activity has been a much larger force of transformative change than changes in climate. On rangelands in particular, which have a long history of transformative change, the pace of change is only accelerating. Drivers of change include overgrazing (Asner *et al*., 2004; Reynolds *et al*., 2007), invasion by non-native species (Masters and Sheley, 2001)(Wilcox 2007; Nagler *et al*., 2008; Stromberg *et al*., 2009) and atmospheric change (Polley *et al*., 2006). The resulting changes on rangelands can be categorized primarily as three interrelated types: woody plant encroachment, invasive species, and desertification (Wilcox and Thurow, 2006).

In a process often described as 'woody plant encroachment,' large tracts of grasslands and savannas have been converted to woodlands. This conversion has resulted from a combination of factors, including overgrazing, reduction in fire frequency, and increases in greenhouse gases (Archer, 1994; Scholes and Archer, 1997; Archer *et al*., 2001; Van Auken, 2009). The ecohydrological implications of this large-scale transformation are not fully understood—or in some cases are misunderstood (Huxman *et al*., 2005; Newman *et al*., 2006). There is a good evidence that a shift from grasses to shrubs leads to a decline in groundwater recharge, but not at a level that would be important for water supply (Scanlon *et al*., 2005). In spite of the common perception that expansion of shrublands leads to appreciable changes in streamflow, there is little if any evidence that this is the case—unless degradation or desertification processes are taking place as well (Wilcox *et al*., 2006). Under degraded conditions, surface runoff will generally be higher than under non-degraded ones (Wilcox *et al*., 2008).

Another dramatic example of transformative landscape change is the invasion of native rangelands by non-native species (Bradley *et al*., 2009). These include forbs such as leafy spurge (*Euphorbia esula*) and spotted knapweed (*Centaurea biebersteinii*); grasses such as cheatgrass (*Bromus tectorum)*, buffelgrass grass (*Pennisetum ciliare*), Lehmann lovegrass (*Eragrostis lehmanniana*), and King Ranch bluestem (*Bothriochloa ischaemum var. songarica*); and riparian shrubs such as salt cedar (*Tamarix* sp.) and Russian Olive (*Elaeagnus angustifolia*). All of these are potentially 'transformative species', capable of altering fundamental ecosystem processes (Evans *et al*., 2001). The invasive annual grasses in particular, with their substantial and highly flammable fuel loads, can alter fire regimes (Melgoza *et al*., 1990; Knapp, 1996; Franklin *et al*., 2006). To date there has been relatively little work examining the large-scale effects of invasive forbs and grasses on the water cycle. One possible (but so far unconfirmed) effect would be increased groundwater recharge in areas where shrubs are replaced by grasses (Seyfried and Wilcox, 2006; Norton *et al*., 2008; Boxell and Drohan, 2009).

Yet another example of transformative landscape change is seen in semiarid riparian zones of the United States that have been invaded by exotic shrubs such as salt cedar (*Tamarix* sp.). The causes and consequences of the expansion of salt cedar have been much debated (Stromberg *et al*., 2009), but a consensus seems to be building that the greatly altered flow regimes of many river systems in the American Southwest is largely responsible (Glenn and Nagler, 2005). Views concerning the hydrological implications of this transformation have been evolving as well. Whereas early work indicated that the costs of shrub expansion were huge in terms of lost water and increased flooding (Zavaleta, 2000), more recent work suggests that there is relatively little potential for water savings through control or eradication of salt cedar (Glenn and Nagler, 2005; Wilcox *et al*., 2006; Owens and Moore, 2007; Nagler *et al*., 2008). Especially if the salt cedar is replaced by native shrubs, gains in streamflow are likely to be negligible (Wilcox *et al*., 2006). Still, in spite these recent findings, public pressure on land-management agencies to restore riparian landscapes altered by exotic shrubs remains strong (Shafroth and Briggs, 2008). It seems certain, however, that management strategies will shift away from attempts at eradication and towards managing flow regimes to give native species a competitive advantage (Rood *et al*., 2005; Richardson *et al*., 2007).

Finally, the most extensive, persistent, and perhaps intractable example of transformative change on rangelands is the process of desertification (Okin *et al*., 2009). By some estimates, up to 20% of drylands are already in a degraded state (Reynolds *et al*., 2007). In some locations, such as the Mediterranean, the degradation process began centuries ago (Brandt and Thornes, 1996). In others it is a relatively recent phenomenon and seems to be accelerating, especially in the developing world (Asner *et al*., 2004). Undeniably, the ecohydrological consequences of desertification for the water, sediment, and biogeochemical cycles are enormous (Dregne, 2000), as are those for the climate itself (Asner and Heidebrecht, 2005; Sivakumar, 2007). Even so, with respect to specific consequences for the water cycle, there is much we do not know—at larger scales in particular. For instance, we know surprisingly little about the effects (if any) of desertification and degradation on river flows (Wilcox, 2007). One of the best documented examples of large-scale hydrological changes as a result of land degradation are the increases in regional runoff and streamflows in the Sahel (Leblanc *et al*., 2008; Favreau *et al*., 2009).

CONCLUSION

The emerging discipline of ecohydrology and the more established one of watershed management are intimately coupled. Both disciplines are being shaped and transformed by the urgent need to understand the ecohydrological consequences of transformative landscape change as well as devising strategies for mitigating them. The rich and diverse research legacy examining the relationship between vegetation management and water yield will provide a solid foundation for meeting these future challenges.

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