15 Applications of Forest Hydrological Science to Watershed Management in the 21st Century

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15.1 Introduction

The remainder of the 21st century will present significant challenges for forest watershed management, as rapid and compounded environmental, economic and social change contribute to an increasingly uncertain future. Many of these changes portend a growing risk of water scarcity for a growing human population and greater vulnerability to extreme droughts and more intense storms. Forest hydrological science has a strong tradition of providing the information required for restoring and managing disturbed and stressed landscapes, positioning the field well to guide management to provide essential ecosystem services in the future. Indeed, the origins of the establishment of public forest lands for the protection of watersheds in the USA under the Weeks Act of 1911 (http://www.foresthistory.org/ASPNET/Policy/WeeksAct/index.aspx, accessed 10 April 2016) reflected a strong recognition of the role of forests in regulating water supply and providing high-quality surface water for aquatic ecosystems and human consumption. Knowledge gained from watershed research and management experience over the past century provides a solid foundation to prepare for future management decisions; however, it is not clear if the past alone will serve as an adequate model. Rates of contemporary landscape modification, climate change and altered disturbance regimes are unprecedented and few watershed ecosystems remain beyond the influence of human activity (e.g. Likens, 2001; Seastedt *et al*., 2008; Hobbs *et al*., 2009). Hydrological cycles have already been altered and changes will continue as climate change, population growth, water diversion and numerous other environmental changes continue (Huntington, 2006; Naiman, 2013). At the same time, there are societal expectations that watershed ecosystems can be managed to maintain functional states (Naiman, 2013). An assessment of how forest hydrology can be applied, adapted and expanded to address these challenges is critical for ensuring that water-based ecosystem services can be sustained in the future.

In this chapter we examine the role of forest hydrological science in the development and application of watershed management in the 21st century. We provide a brief synthesis of anticipated biophysical and socio-economic changes expected to occur over the coming decades and discuss critical watershed science needs and management responses to maintain watershed

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ecosystem services in the coming decades. We build on several recent discussions (e.g. National Research Council, 2008; Riveros-Iregui *et al*., 2011; Vose *et al*., 2012; Wang *et al*., 2012; Egginton *et al*., 2014) on the role of ecohydrology in addressing water resource challenges now and in the future. We focus our examples on forest watersheds in the southern US forests, as the complex mixture of public and private forest land ownership creates substantial challenges for watershed management at larger spatial scales. Despite the focus on the southern USA, the general principles are applicable to forest watersheds across the globe.

The last century of forest watershed research has provided a fundamental understanding of watershed hydrological processes and best management practices (BMPs) that either protect or restore these processes when watersheds are managed. The state-of-the-knowledge on forest watershed science has been summarized by Ice and Stednick (2004) for the continental USA, Lockaby *et al*. (2013) for the southern USA and de la Crétaz and Barten (2007) for the north-eastern USA. These summaries provide the following five key lessons for watershed management:

1. Forests provide the cleanest and most stable flows of surface water and groundwater recharge among all land uses.
2. Flow amount (water yield) and timing can be altered by forest management; flows can increase or decrease depending upon post-disturbance successional patterns.
3. Nutrient levels in forested watersheds are generally low; however, sediment loading can increase when disturbance results in erosion and sediment delivery.
4. Riparian areas and forested wetlands are especially important for regulating flows and protecting water quality.
5. The implementation of BMPs is critical for ensuring that forests can be managed to avoid or minimize adverse effects on water resources.

A recent National Research Council (2008) review assessed the applicability of these cornerstones and concluded that detailed understanding of hydrological processes and land-use effects at the experimental watershed scale is strong for comparatively short time periods (i.e. 5 to 15 years), but our understanding diminishes rapidly as spatial and temporal scales increase (e.g. to ecoregions, multiple decades). Hence, in this chapter we ask: (i) how will large-scale changes in land use and long-term changes in climatic conditions affect our ability to formulate and implement watershed management policies, plans and practices; and (ii) what new research questions and approaches will be needed to address critical information gaps and uncertainty? We address these questions by focusing on how our current understanding of forest watershed responses to management practices can be applied to sustain water resources and what new management approaches might be required. We consider the shift from a forest management philosophy in the eastern USA of avoiding water quality impacts to a more comprehensive view of forests as a vitally important land cover and land use required to sustain aquatic ecosystems, water supplies and public health (*sensu* Postel and Richter, 2003).

15.2 Biophysical and Socio-Economic Changes Expected to Occur Over the Coming Decades

Changes in earth systems including atmospheric chemistry, nutrient and hydrological cycling resulting from human activities are significant enough to define a new geological epoch, the Anthropocene. Marking the end of the Holocene, the most recent 10,000- to 12,000-year interglacial period, there is some debate as to whether the Anthropocene began circa 1800 with the Industrial Revolution, in the post-war era of the 1950s, or about using those dates as the beginning of two stages (Steffen *et al*., 2007). This is because human effects on atmospheric chemistry can be traced back to initial industrialization and the associated use of fossil fuels, beginning with coal-powered steam engines. By 1950, the concentration of atmospheric CO_2 had increased to 310 ppm from pre-industrial levels of 270–275 ppm (Steffen *et al*., 2007). During the second half of the 20th century, the world population doubled and became more urbanized, global economic activity increased 15-fold and anthropogenic sources of reactive nitrogen (fertilizers, fossil fuel combustion) surpassed the sum of all natural production (Steffen *et al*., 2007). Atmospheric CO_2 has surpassed 400 ppm and is increasing at an accelerating rate, accumulating an additional 2.25 ppm/year today – compared with 0.75 ppm/year in 1959 (Field *et al*., 2014).

The Anthropocene will continue to be an era of significant and rapid change as the primary driving factors, human population growth and development, continue to accelerate. By 1950, temperate broadleaf and mixed forests covered less than half the earth surface capable of supporting this biome, and by 2050 it is estimated that another 10% will be lost (Millennium Ecosystem Assessment, 2005). This is due in part to an expected world population of 9.5 billion by 2050, a 36% increase from 2010 (United Nations, 2013). As the population grows, urban growth and development will continue as, by 2050, 66% of the world population is expected to live in urban areas, a 12% increase from 2014 (United Nations, 2014). In the Southeast USA, 12–17 million ha of additional development are expected by 2060, which represents at least twice the present area of urban land cover (Wear, 2013). Urban growth will be particularly concentrated in the Southern Appalachian Piedmont, creating a connected urban corridor from Richmond, Virginia through Raleigh–Durham, North Carolina to Atlanta, Georgia (Wear and Greis, 2013; Terrando *et al*., 2014). The increasing population will result in increased water demand. If current patterns of development continue across the region, the effects of urbanization will be exacerbated by low-density development ('sprawl') that increases the connectivity of developed areas while fragmenting and isolating natural areas (Terrando *et al*., 2014). This translates to a loss of between 7 and 13% of regional forestland across the Southeast, with losses up to 21% in the Southern Appalachian Piedmont subsection (Wear, 2013). As forest is replaced by urban uses, concentrations of sediment, nutrients, pollutants and pathogens all increase and degrade water quality (Lockaby *et al*., 2013). Population growth and development also affect water availability; by 2050, water stress (defined as human demand divided by water supply) is expected to increase by 10% across the Southeast. As forest is lost, forest types are also expected to shift, with planted pine replacing much of the remaining natural pine (Huggett *et al*., 2013).

In addition to development and rapid land-use change, the Anthropocene is an era of rapid climate change. Global average temperatures are estimated to have risen by 0.65–1.06°C between 1880 and 2012 (Field *et al*., 2014). This trend is expected to continue, with an additional increase of up to 4.8°C in global average temperature by the end of the century (Field *et al*., 2014). In the Southeast, average temperatures have increased by just over 1°C since 1970, with greater increases during the summer (Carter *et al*., 2014). In the near future, the Southeast is expected to have a more variable climate with temperatures increasing by approximately 2 to 4°C and more days exceeding 35°C by the end of the century (McNulty *et al*., 2013). Precipitation forecasts are more variable and while some models suggest minimal change, this could be an artefact of the regional position between the Southwest, where precipitation is expected to decrease, and the Northeast, where precipitation is expected to increase (Carter *et al*., 2014). Even with the uncertainty of precipitation models, greater evaporative loss from increased temperatures may increase water stress. Most general circulation models predict that the frequency of extreme precipitation events will increase worldwide as the climate warms (O'Gorman and Schneider, 2009), likely increasing the magnitude and frequency of both flood events (overbank flow) and drought (both meteorological and hydrological). Many regions of the USA have recorded an increased frequency of precipitation extremes (i.e. more droughts and larger, high-intensity rainfall events) during the last 50 years (Easterling *et al*., 2000; Huntington, 2006; Field *et al*., 2014). The timing and spatial distribution of extreme or low-probability events are among the most uncertain aspects of future climate scenarios. Forecasts are complicated by natural variability of inter- and intra-annual precipitation across the continental USA related to large-scale global climate teleconnections (e.g. El Niño Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation) (Karl *et al*., 1995; Allen and Ingram, 2002).

Extreme precipitation events are not the only sources of future uncertainty and variation; novel and compounded disturbances are expected to accelerate in the future. For example, climate change is expected to increase fire activity (Marlon *et al*., 2008). Increasing temperatures and the resulting drier conditions will also increase wildfire risk, in part because of extended fire seasons. By 2060 in the Southeast USA, climate change is expected to increase the frequency and intensity of wildfires and extend fire seasons by up to 3 months (Liu *et al.*, 2013). Large, high-intensity wildfires are uncommon in the region because of the effectiveness of long-term prescribed fire, fuel load reduction and wildfire suppression programmes. Hotter, drier conditions could limit the number of days that meet the criteria for controlled burning, thereby limiting the opportunity for fuel load reduction and proactive fire management (Melvin, 2012; Liu *et al.*, 2013; Mitchell *et al.*, 2014). Further, under extreme future conditions, some fires will likely burn at high intensity regardless of prescribed fire management. This was the case in 2007, when the Georgia Bay Complex fires burned as crown fires through the Osceola National Forest, even in stands that had been treated with prescribed fire in the previous five years (Fites *et al.*, 2007). Severe wildfires can cause increased runoff and erosion by removing litter and duff layers, altering soil permeability and reducing evapotranspiration because of high tree mortality (Ice *et al.*, 2004; Certini, 2005; Doerr *et al.*, 2006). Future fire risk is also dependent upon future fuel dynamics, of which pests, diseases and invasive species are an increasingly important component. Pests and diseases amplify fire risk by causing mortality and, thus, increasing fuel loads. This is also true of some invasive species. For example, cogongrass (*Imperata cylindrica*) is a highly flammable invasive spreading rapidly throughout the Southeast (Bradley *et al.*, 2010).

In the Southeast, 9% of the forest contains at least one invasive species, with an annual spread rate exceeding 58,000 ha (Miller *et al.*, 2013). Many successful plant invaders are rapidly growing species with high evapotranspiration rates that increase water fluxes. In the western USA, *Tamarix* invasions have increased transpirational water fluxes and, in consequence, decreased streamflow (Ehrenfeld, 2010). Although invasive plants with such a substantial effect are not yet present in the Southeast, the invasion of hemlock woolly adelgid (*Adelges tsugae*) alters hydrological cycling by removing eastern hemlock (*Tsuga canadensis*), an evergreen riparian tree (Ford and Vose, 2007; Brantley *et al.*, 2015). The effects of invasive species on ecosystem structure and function are increasingly well documented (Lovett *et al.*, 2006; Ehrenfeld, 2010). However, less is understood about how novel or hybrid communities of multiple invasive species affect ecosystem functions (Hobbs *et al.*, 2006, 2009).

Novel ecosystems are increasing across landscapes as consequences of the Anthropocene, where nearly all ecosystems are affected by human activity. As defined by Hobbs *et al.* (2006), novel ecosystems are characterized by species combinations that have not previously occurred in a biome, are a result of either direct or indirect human actions, and have become self-perpetuating. Many of these ecosystems are so different from earlier successional patterns and species assemblages that restoration efforts are unlikely or very difficult. It is, therefore, more likely that urban and suburban areas will, in some cases, need to be managed as novel or hybrid ecosystems to maintain ecological services, including water resources (Hobbs *et al.*, 2014).

15.3 Management Responses to Maintain Watershed Ecosystem Services in the 21st Century

While we expect that many of the principles of forest hydrological science derived from the previous century will continue to be highly relevant and applicable for the remainder of the 21st century, we propose that the rapid pace and scale of biophysical and socio-economic changes expected over the coming decades will require a combination of modified and new management approaches to maintain ecosystem services. For example, modifications of current BMPs to address greater precipitation variability might include wider riparian buffers, larger culverts at road crossings, and more efficient and stable road design. The need for new management approaches is driven in large part by the growing demand for freshwater. Water derived from forests has always been considered a valuable ecosystem service and watershed protection to maintain water quality was a primary focus. In the future, increasing demand for freshwater will likely place a greater emphasis on managing forests for water yield. Large-scale management may be necessary to meet the needs of an increasingly urbanized landscape. In the following section, we discuss two critical areas where forest hydrological science will need to advance to inform and support management responses (Vose *et al*., 2012).

15.3.1 Managing species composition and stand structure to optimize water yield

The potential impacts of increased climate variability such as droughts and heavy rainfall events will be determined by the balance between precipitation (P) inputs versus tree water demand (potential evapotranspiration or PET) in the future. For example, forested areas in the arid Southwest are characterized by low P/PET ratios (<1), forested areas in the Northeast and Northwest are characterized by high P/PET ratios (>1), and large areas in the South USA have P/PET ratios near unity (Plate 13). Current ecological, socio-economic and watershed management systems have evolved in response to this balance between precipitation and potential evapotranspiration. In areas where precipitation greatly exceeds potential evapotranspiration, water is generally abundant, mesic species are favoured, and the management focus is on flooding and water quality protection. In contrast, in areas where potential evapotranspiration greatly exceeds precipitation, water is limiting, xeric species are favoured, and the management focus is on managing dry periods and associated disturbances such as wildfire and on developing reliable water supply sources for agriculture and human needs. Future scenarios suggest it is likely that at mid-latitudes, wet areas will generally get wetter and the dry areas will generally get drier (Field *et al*., 2014). However, even if overall precipitation does not change, higher air temperatures will amplify the effects of droughts when they occur (Breshears *et al*., 2005). In the southern USA, the high diversity of tree species and the ability to actively manage forests over much of the landscape provide a unique opportunity to develop or refine optimal watershed management strategies to protect water quality and, potentially, to increase or sustain water yields.

Forests in the eastern USA are changing and these changes can affect water yield, quality and timing. Many areas of the Southeast have gained additional forested area over the 20th century as agricultural land use declined, and evapotranspiration has likely increased as a result (Kim *et al*., 2014). In addition, forest species transitions have occurred due to purposeful management activities such as the establishment of plantation forests, but also due to successional processes and altered disturbance regimes. For example, from the early part of the 20th century, species composition in oak and oak–pine forests has transitioned throughout the eastern USA, a process that has been characterized as mesophication (Nowacki and Abrams, 2015). This term is used to describe a shift in dominance away from species that tended to thrive in more xeric conditions with shorter fire rotations (e.g. thick-barked oak species). There are many potential factors that have contributed to this change, including wetter conditions, fire suppression and the maturation of much of the forest following widespread harvests during the 20th century (McEwan *et al*., 2011; Nowacki and Abrams, 2008, 2015).

This change in species composition alters vulnerability to drought and the relative magnitude of water balance components through changes in evapotranspiration, both in terms of interception and transpiration (Zhang *et al*., 2001). Physical canopy architecture, tree height and duration (evergreen versus deciduous) all affect interception rates (Calder *et al*., 2003). Shorter trees have higher interception rates than taller trees of the same species, and evergreen species tend to have higher interception rates compared with deciduous species (Rutter *et al*., 1975; Calder *et al*., 2003; Ford *et al*., 2011). In the Southeast, Ford *et al*. (2011) found that interception was almost twice as high in plantation pine stands (*Pinus strobus*) compared with mixed hardwood stands. Ford *et al*. (2011) also found that transpiration has a greater effect on evapotranspiration than interception, and transpiration is particularly important in dry years. Xylem anatomy and the resulting sapwood area are important determinants of stand transpiration (Wullschleger *et al*., 2001; Ford *et al*., 2007). Mesophytic species are typically diffuse porous and have greater sapwood area than ring- or semi-ring porous species. As sapwood area increases, potential water transport increases (Enquist *et al*., 1998; Meinzer *et al*., 2005). For example, transpiration rates for a given diameter yellow poplar (*Liriodendron tulipifera*) (diffuse porous xylem) are nearly twofold greater than for hickory (*Carya* spp.) (semi-ring porous) and fourfold greater than for oaks (*Quercus* spp.) (ring porous xylem) (Fig. 15.1). In addition, transpiration and stomatal conductance rates of diffuse porous species are also much more responsive to climatic variation compared with ring-porous species such as oaks and hickories (Ford *et al.*, 2007). When droughts are severe, diffuse porous, mesophytic species have higher mortality rates than ring porous species (Klos *et al.*, 2009). Watershed data also suggest that pine forests in general, and southern pine plantations specifically, have greater evapotranspiration, due to higher interception and transpiration, than corresponding hardwood forests (Ford *et al.*, 2011) and are more vulnerable to drought (Domec *et al.*, 2015).

Taken together, these findings suggest that forests in the southern USA are using more water now than in the past and that they could be more vulnerable to drought in the future. As such, it might be expected that streamflow gauges would detect decreasing trends in long-term streamflow; however, numerous factors influence streamflow, so establishing a simple cause-and-effect relationship is challenging, especially at large spatial scales. For example, studies have detected both decreasing and increasing flows in the southern USA, which could be due in part to precipitation variability (Patterson *et al.*, 2013; Kim *et al.*, 2014; Yang *et al.*, 2014). Despite this variability in observations, management that shifts southern forests back towards more ring porous, drought-tolerant species might increase water yield and provide resilience to future drought. This change in species could be encouraged through increased use of prescribed fire, which should favour *Quercus* spp. and reduce mesophytic species. However, treatments must be repeated regularly and in some cases combined with manipulation such as thinning to achieve changes in relative species abundances (Green *et al.*, 2010; Martin *et al.*, 2011; Arthur *et al.*, 2015). In addition to prescribed fire, particularly in areas that cannot be burned, forest thinning could remove mesophytic species and favour water-efficient and drought-tolerant species.

Pine plantations are an important forest type in the southern USA, providing fibre and solid timber products for the region, nation and globe (Wear and Greis, 2013). Decades of research have resulted in genetic improvements and silvicultural practices (e.g. site preparation, fertilization, thinning, weed control) that have

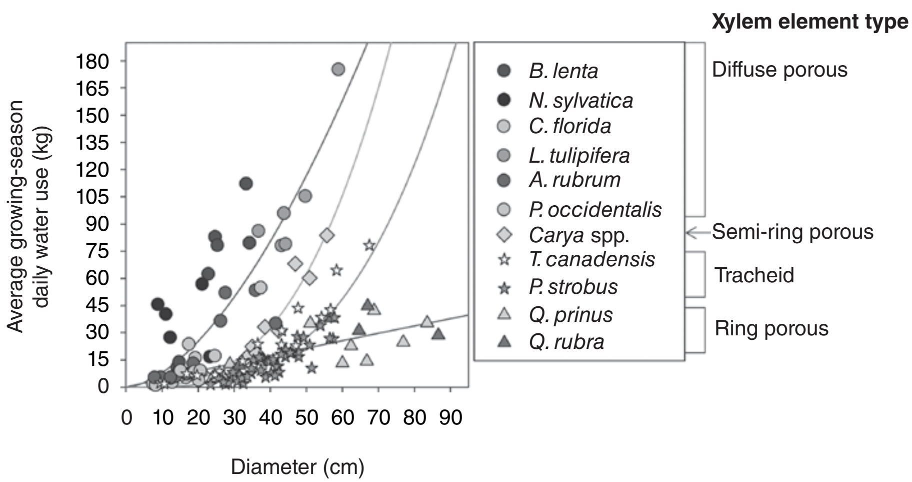

Fig. 15.1. Mean growing-season daily water use across forest species with different xylem anatomy in the southern USA. Full names for the species listed are: *Betula lenta, Nyssa sylvatica, Cornus florida, Liriodendron tulipifera, Acer rubrum, Platanus occidentalis, Tsuga canadensis, Pinus strobus, Quercus prinus* and *Quercus rubra*. (From Ford *et al.*, 2011.)

substantially increased productivity (Fox *et al*., 2007) of southern pine plantations; however, these highly productive forests also tend to use more water (Jackson *et al*., 2005; Ford *et al*., 2011; King *et al*., 2013) and are more vulnerable to drought (Domec *et al*., 2015; Ward *et al*., 2015). Some suggest that the acres planted in pine will increase in the future (e.g. Huggett *et al*., 2013), with values ranging from an increase of 20 to 25 million ha by 2060, depending upon assumptions related to climatic and economic conditions (e.g. global forest products markets, biomass energy). Where and when water is plentiful, it is unlikely that this expansion will have adverse effects on water resources. However, under more variable rainfall or in areas where water is (or will be) increasingly scarce, expansion of pine plantations or other fast-growing trees could have negative effects on water resources (Calder *et al*., 2009; King *et al*., 2013; Vose *et al*., 2015). Alternatives include managing plantations with lower stocking (Sun *et al*., 2015) or managing for species that use less water (Calder *et al*., 2009), such as restoring longleaf pine (Lockaby *et al*., 2013).

Management actions can also be implemented to minimize the impacts of drought on water quality. In more developed areas, an obvious measure is to limit stream water withdrawals (Webb and Nobilis, 1995; Meier *et al*., 2003) and, if possible, wastewater discharge during periods of low flow, and encourage re-use of treated wastewater to help reduce higher-temperature effluent volume entering streams (Kinouchi, 2007). In forested areas, efforts should focus on minimizing inputs of sediments and nutrients into the stream. It may be beneficial to plan the timing of management activities so they do not disturb streams during low flow. Since removal and alteration of riparian vegetation increases stream temperatures (Beschta *et al*., 1987; Groom *et al*., 2011) following timber harvest (Swift and Messer, 1971; Swift and Baker, 1973; Wooldridge and Stern, 1979; Sun *et al*., 2004) and wildfires (Dunham *et al*., 2007; Isaak *et al*., 2010), maintaining or increasing shading effects of riparian forest canopy reduces fluctuations in water temperature, dissolved oxygen concentrations and stress (both acute and chronic) on aquatic organisms (Burton and Likens, 1973; Swift and Baker, 1973; Peterson and Kwak, 1999; Kaushal *et al*., 2010).

15.3.2 Managing at larger spatial scales

Forest management for water resources should attempt to address the landscape scale of major river systems. In the Southeast USA, growing metropolitan areas of the Piedmont are dependent upon watersheds that originate in the largely forested Mountain region. Downstream of the rapidly urbanizing Piedmont, the Coastal Plain includes large areas of agriculture and plantation forestry. Water supply and management systems are embedded in this matrix of forest, urban and agricultural landscapes. This complex, but interconnected landscape provides a broader context for forest management. As the growing human population becomes increasingly urbanized and demand for freshwater increases, we expect a greater need for forest watershed management options to provide a stable supply of freshwater. The concept of managing forests at large spatial scales to augment annual streamflow is not new (Douglass, 1983); however, recent severe drought in many areas of the USA has increased awareness of the relationship among forest disturbance and management, drought and streamflow (Ford *et al*., 2011; Jones *et al*., 2012). Since harvesting often increases annual water yield, it has been suggested that the effects of drought could be mitigated by maintaining lower-density forests (McLaughlin *et al*., 2013). Less-dense forests might provide increased water yield while reducing water stress on trees during drought.

While we have a good understanding of the effects of disturbance and forest management on water yield from studies on small watersheds, it is not clear if effects can simply be scaled up and results extrapolated over larger spatial scales (National Research Council, 2008). Tools such as remote sensing, GIS and networks of sensors can facilitate studies across larger spatial scales. In addition, hydrological models are an important tool for scaling across space and time, and they can also be used for retrospective analyses of complex systems and to generate future scenarios, identify critical knowledge gaps and generate new hypotheses. As an example, we used RHESSys, a regional hydro-ecological simulation system (Tague and Band, 2004) to further examine the potential for using forest management to increase water yield at larger spatial scales. The RHESSys model has been used to assess the effects of climate, fire and urbanization on water resources across multiple ecosystems (e.g. Tague *et al.*, 2009; Mittman *et al.*, 2012; Godsey *et al.*, 2014; Hwang *et al.*, 2014; Vicente-Serrano *et al.*, 2015). As a case study, we used the Beetree Creek watershed, which is a 1414 ha watershed in the Appalachian Mountains of western North Carolina where streamflow has been recorded daily by a US Geological Survey gauge since 1926. Runoff from Beetree Creek collects in a reservoir that serves as a secondary drinking-water source for the city of Asheville, North Carolina. Over a 6-year simulation period, we found that a 50% reduction of forest density, with a 30 m riparian buffer, mitigated the effects of a 20% reduction in precipitation, although the effects seemed to decline in the last year (Fig. 15.2a). When we removed all precipitation in June–August to simulate an extreme summer drought, the same 50% reduction in forest density with a riparian buffer still exhibited a mitigating effect, particularly during the dormant season, likely due to soil water storage (Fig. 15.2b). This might be a significant contribution during dry periods, particularly in watersheds such as this one that are part of a municipal water supply.

Although it is clear that streamflow can be altered with forest management, major challenges remain in managing forests to enhance water supply. First, a large proportion of the watershed has to be cut in order to increase

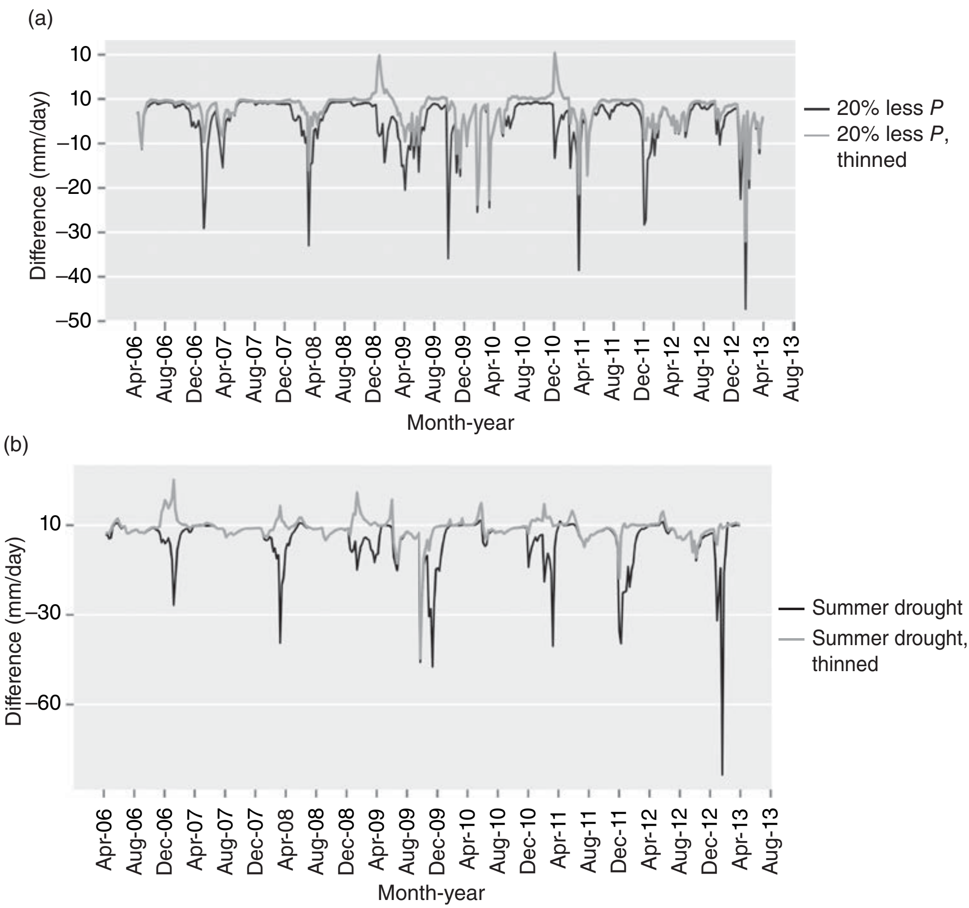

Fig. 15.2. RHESSys simulations comparing baseline water yield (*Q*) to harvest treatments (50% forest reduction, leaving 30 m riparian buffer) under (a) a 20% reduction in precipitation (*P*) and (b) an extreme summer drought, with no precipitation in June–August.

annual water yield at large spatial scales (Bosch and Hewlett, 1982; Ice and Stednick, 2004). Consequently, the potential increases in streamflow through forest cutting are minimal due to limitations on the amount of land that can be harvested at any given time (Kattelmann *et al.*, 1983). Our simulation experiment was conducted on a small (1414 ha) watershed; this harvest likely had little or no detectable effect downstream or on the overall 481,220 ha Upper French Broad River watershed. In addition, streamflow responses are often short-lived due to rapid forest regrowth (especially in the eastern USA; Swank *et al.*, 2014) and the aggrading post-cut forest may actually have lower streamflow than the uncut forest (Ford *et al.*, 2011). And, because of the unpredictable nature of droughts, it is impractical to time harvesting operations as a drought response strategy to maintain streamflow. In contrast to management actions that are intended to augment streamflow, increasing drought stress in some forest ecosystems may warrant management strategies that retain water (and hence reduce streamflow) on the landscape in order to minimize tree mortality (Grant *et al.*, 2013). Even in cases where thinning might not increase streamflow, lower-density forests are likely to be more resistant and resilient to drought conditions, allowing the majority of trees to survive and resume ecosystem service production in the future. Further, replanting or regenerating harvested forests with species that consume less water is a longer-term solution that may be more effective in some cases, so long as it is economically feasible and does not adversely affect other forest management objectives, such as forest productivity, carbon sequestration, wildlife habitat and water quality (King *et al.*, 2013).

Overall, our experiments simulating reduced precipitation and an extreme drought (Fig. 15.2a and b) support suggestions that future conditions might at times exceed the capacity of forests to provide ecosystem services, including water resources. Therefore, management of coupled social–ecological systems must include water use and storage strategies to bridge the gaps created by extreme conditions during severe or extended droughts. For example, municipalities will need strategies to maintain water supplies, such as reducing consumption, increasing conservation, adding additional emergency sources or creating additional storage.

15.4 Conclusions and Recommendations

The remainder of the 21st century will present significant challenges for forest watershed management, as rapid and compounded biophysical and socio-economic changes contribute to an increasingly uncertain future. Many of these changes portend a growing risk of water scarcity for a growing human population and greater vulnerability to extreme droughts and more intense storms. A century of forest watershed science has been critical for ensuring the sustainability of water resources derived from forest watersheds. We know with certainty that forest vegetation has a strong influence over the water balance and hydrological and biogechemical cycling processes and that BMPs must be implemented to protect water resources in managed forests. A key question is whether our current understanding, tools and management practices will be applicable in the remainder of the 21st century.

We propose that much of our understanding of forest hydrological processes and how to manage forest watersheds accordingly will continue to be applicable; however, the rapid pace and magnitude of change will constrain management outcomes. We expect that forests will continue to remain a better land-use choice compared with non-forest alternatives for clean, stable water resources, but new adaptive management regimes may be needed to reduce water demand and maintain forests on the landscape. Although it is understood that processes like evapotranspiration, water yield and timing are affected by forest management, the duration and spatial scale of these effects merit further investigation (National Research Council, 2008). Projections indicate a future of increasing pine plantations and expansion of fast-growing species for carbon sequestration and bioenergy, but landscape-scale effects on water yield and quality, and the magnitude of potential trade-offs between managing for carbon and water, have not been systematically explored across time and space (Jackson *et al.*, 2005; King *et al.*, 2013). The likelihood of increasing water scarcity will require a better understanding of how to manage forest structure and species composition for both maximum water yield and minimized tree mortality. Forests changes in the eastern USA (i.e. via succession and intensive forest management) have created forests that require more water and are more drought-prone. The challenge of managing forests at large spatial scales suggests a need to identify if and where management would be particularly effective in increasing water yield and, thus, water supplies. Further research could also identify the most drought-vulnerable areas so that management could be prioritized to increase forest resilience. Modelling studies provide a valuable tool for examining potential short- and long-term consequences of forest management on water resources, forest resilience and other ecosystem services, including carbon sequestration and wood and fibre production, at landscape scales. However, modelling must be accompanied by continued or additional monitoring not only of small watersheds, but large ones as well. When and where possible, experiments nested across larger watersheds using an adaptive management approach would provide the most realistic and useful information.

References

Allen, M.R. and Ingram, W.J. (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature* 419, 224–232.

Arthur, M.A., Blankenship, B.A., Schorgendorfer, A., Loftis, D.L. and Alexander, H.D. (2015) Changes in stand structure and tree vigor with repeated prescribed fire in an Appalachian hardwood forest. *Forest Ecology and Management* 340, 46–61.

Beschta, R.L., Bilby, R.E., Brown, G.W., Holtby, L.B. and Hofstra, T.D. (1987) Stream temperature and aquatic habitat: fisheries and forestry interactions. In: Salo, E.O. and Cundy, T.W. (eds) *Streamside Management: Forestry and Fishery Interactions*. Contribution No. 57. University of Washington Institute of Forest Resources, Seattle, Washington, pp. 191–232.

Bosch, J.M. and Hewlett, J.D. (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55, 3–23.

Bradley, B.A., Wilcove, D.S. and Oppenheimer, M. (2010) Climate change increases risk of plant invasion in the Eastern United States. *Biological Invasion* 12, 1855–1872.

Brantley, S.T., Miniat, C.F., Elliott, K.J., Laseter, S.H. and Vose, J.M. (2015) Changes to southern Appalachian water yield and stormflow after loss of a foundation species. *Ecohydrology* 8, 518–528.

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Ballice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., *et al*. (2005) Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Science USA* 102, 15144–15148.

Burton, T.M. and Likens, G.E. (1973) Effect of strip-cutting on stream temperatures in Hubbard Brook Experimental Forest, New Hampshire. *BioScience* 23, 433–435.

Calder, I.R., Reid, I., Nisbet, T.R. and Green, J.C. (2003) Impact of lowland forests in England on water resources: application of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research* 39, 1319, doi: 10.1029/2003WR002042 (accessed 10 April 2016).

Calder, I.R., Nisbet, T. and Harrison, J.A. (2009) An evaluation of the impacts of energy tree plantations on water resources in the United Kingdom under present and future UKCIP02 climate scenarios. *Water Resources Research* 45, W00A17, doi: 10.1029/2007WR006657 (accessed 10 April 2016).

Carter, L.M., Jones, J.W., Berry, L., Burkett, V., Murley, J.F., Obeysekera, J., Schramm, P.J. and Wear, D. (2014) Southeast and the Caribbean. In: Melillo, J.M., Richmond, T.C. and Yohe, G.W. (eds) *Climate Change Impacts in the United States: The Third National Climate Assessment*. US Global Change Research Program, Washington, DC, pp. 396–417.

Certini, G.G. (2005) Effects of fire on properties of forest soils: a review. *Oecologia* 143, 1–10.

De la Crétaz, A.L. and Barten, P.K. (2007) *Land Use Effects on Streamflow and Water Quality in the Northeastern United States*. CRC Press/Taylor & Francis, Boca Raton, Florida.

Doerr, S.H., Shakesby, R.A., Blake, W.H., Chafer, C.M., Humphreys, G.S. and Wallbrink, P.J. (2006) Effects of differing wildfire severities on soil wettability and implications for hydrological response. *Journal of Hydrology* 319, 295–311.

Domec, J.J., King, J.S., Ward, E., Oishi, A.C., Palmroth, S., Radecki, A., Bell, D.M., Miao, G., Gavazzi, M., Johnson, D.M., *et al*. (2015) Conversion of natural forests to managed forest plantations decreases tree resistance to prolonged droughts. *Forest Ecology and Management* 355, 58–71.

Douglass, J.E. (1983) The potential for water yield augmentation from forest management in the eastern United States. *Water Resources Bulletin* 9, 351–358.
Dunham, J.B., Rosenberger, A.E. and Luce, C.H. (2007) Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. *Ecosystems* 10, 335–346.
Easterling, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E. and Ambenje, P. (2000) Observed variability and trends in extreme climate events: a brief review. *Bulletin of the American Meteorological Society* 81, 417–425.
Egginton, P., Beall, F. and Buttle, J. (2014) Reforestation – climate change and water resource implications. *The Forestry Chronicle* 90, 516–524.
Ehrenfeld, J.G. (2010) Ecosystem consequences of biological invasions. *Annual Review of Ecology, Evolution and Systematics* 41, 59–80.
Enquist, B.J., Brown, J.H. and West, G.B. (1998) Allometric scaling of plant energetics and population density. *Nature* 395, 163–165.
Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.K. Masterandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., *et al*. (eds) (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectorial Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovenmental Panel on Climate Change*. Cambridge University Press, Cambridge/New York.
Fites, J.A., Carol, E., Vaillant, N., Campbell, M., Courson, M., Decker, T., Lew, C., Marouk, S., Taylor, Z. and Anderson, R. (2007) Big Turnaround and Georgia Bay Complexes Fire Behavior Assessment Report. USDA Forest Service Fire Behavior Assessment Team. Available at: http://www.fs.fed.us/adaptivemanagement/reports/fbat/GA_Wildfires_2007_detail_report_AMSET.pdf (accessed 10 April 2016).
Ford, C.R. and Vose, J.M. (2007) *Tsuga canadensis* (L.) Carr. mortality will impact hydrologic processes in southern Appalachian forest ecosystems. *Ecological Applications* 17, 1156–1167.
Ford, C.R., Hubbard, R.M., Kloeppel, B.D. and Vose, J.M. (2007) A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balance. *Agricultural and Forest Meteorology* 145, 176–185.
Ford, C.R., Hubbard, R.M. and Vose, J.M. (2011) Quantifying structural and physiological controls on canopy transpiration of planted pine and hardwood stand species in the Southern Appalachians. *Ecohydrology* 4, 183–195.
Fox, T.R., Jokela, E.J. and Allen, H.L. (2007) The development of pine plantation silviculture in the Southern United States. *Journal of Forestry* 105, 337–347.
Godsey, S.E., Kirchner, J.W. and Tague, C.L. (2014) Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA. *Hydrological Processes* 28, 5048–5064.
Grant, G.E., Tague, C.L. and Allen, C.D. (2013) Watering the forest for the trees: an emerging priority for managing water in forest landscapes. *Frontiers in Ecology and the Environment* 11, 314–321.
Green, S.R., Arthur, M.A. and Blankenship, B.A. (2010) Oak and red maple seedling survival and growth following periodic prescribed fire on xeric ridgetops on the Cumberland Plateau. *Forest Ecology and Management* 259, 2256–2266.
Groom, J.D., Dent, L., Madsen, L.J. and Fleuret, J. (2011) Response of western Oregon (USA) stream temperatures to contemporary forest management. *Forest Ecology and Management* 262, 1618–1629.
Hobbs, R.J., Arico, S., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V.A., Epstein, P.R., Ewel, J.J., Klink, C.A., Lugo, A.E., *et al*. (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography* 15, 1–7.
Hobbs, R.J., Higgs, E. and Harris, J.A. (2009) Novel ecosystems: implications for conservation and restoration. *Trends in Ecology and Evolution* 24, 599–605.
Hobbs, R.J., Higgs, E., Hall, C.M., Bridgewater, P.M., Chapin, F.S. III, Ellis, E.C., Ewel, J.J., Hallett, L.M., Harris, J., Hulvey, K.B., *et al*. (2014) Managing the whole landscape: historical, hybrid, and novel ecosystems. *Frontiers of Ecology and the Environment* 12, 557–564.
Huggett, R., Wear, D.N., Li, R., Coulston, J. and Liu, S. (2013) Forecasts of forest conditions. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Futures Project*. General Technical Report 178. USDA Forest Service, Southern Research Station, Asheville, North Carolina, pp. 73–101.
Huntington, T.G. (2006) Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319, 83–95.
Hwang, T., Band, L.E., Miniat, C.F., Song, C., Bolstad, P.V., Vose, J.M. and Love, J.P. (2014) Divergent phonological response to hydroclimate variability in forested mountain watersheds. *Global Change Biology* 20, 2580–2595.

Ice, G.G. and Stednick, J.D. (2004) *A Century of Forest and Wildland Watershed Lessons*. Society of American Foresters, Bethesda, Maryland.

Ice, G.G., Neary, D.G. and Adams, P.W. (2004) Effects of wildfire on soils and watershed processes. *Journal of Forestry* 102, 16–20.

Isaak, D.J., Luce, C.H., Rieman, B.E., Nagel, D.E., Peterson, E.E., Horan, D.L., Parkes, S. and Chandler, G.L. (2010) Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications* 20, 1350– 1371.

Jackson, R.B., Jabbogy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., Carl, B.A. and Murray, B.C. (2005) Trading water for carbon with biological carbon sequestration. *Science* 310, 1944–1947.

Jones, J.A., Creed, I.F., Hatcher, K.L., Warren, R.J., Adams, M.B., Benson, M.H., Boose, E., Brown, W.A., Campbell, J.L., Covich, A., *et al*. (2012) Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. *BioScience* 62, 390–404.

Karl, T.R., Knight, R.W. and Plummer, N. (1995) Trends in high-frequency climate variability in the twentieth century. *Nature* 377, 217–220.

Kattelmann, R.C., Berg, N.H. and Rector, J. (1983) The potential for increasing streamflow from Sierra-Nevada watersheds. *Water Resources Bulletin* 19, 395–402.

Kaushal, S.S., Likens, G.E., Jaworski, N.A., Pace, M.L., Sides, A.M., Seekell, D., Belt, K.T., Secor, D.H. and Wingate, R.L. (2010) Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment* 8, 461–466.

Kim, Y., Band, L.E. and Song, C. (2014) The influence of forest regrowth on the stream discharge in the North Carolina Piedmont watersheds. *Journal of the American Water Resources Association* 50, 57–73.

King, J.S., Ceulemans, R., Albaugh, J.M., Dillen, S.Y., Docmec, J.C., Fichot, R., Fischer, M., Leggett, Z., Sucre, E., Trnka, M. and Zenone, T. (2013) The challenge of lignocellulosic bioenergy in a water-limited world. *BioScience* 63, 102–117.

Kinouchi, T. (2007) Impact of long-term water and energy consumption in Tokyo on wastewater effluent: implications for the thermal degradation of urban streams. *Hydrological Processes* 21, 1207–1216.

Klos, R.J., Wang, G.G., Bauerle, W.L. and Rieck, J.R. (2009) Drought impact on forest growth and mortality in the southeast USA: an analysis using Forest Health and Monitoring data. *Ecological Applications* 19, 699–708.

Likens, G. (2001) Biogeochemistry, the watershed approach: some uses and limitations. *Marine and Freshwater Research* 52, 5–12.

Liu, Y.Q., Goodrick, S.L. and Stanturf, J.A. (2013) Future US wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management* 294, 120–135.

Lockaby, G., Nagy, C., Vose, J.M., Ford, C.R., Sun, G., McNulty, S., Caldwell, P., Cohen, E. and Myers, J.M. (2013) Forests and water. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Futures Project.* General Technical Report 178. USDA Forest Service, Southern Research Station, Asheville, North Carolina, pp. 309–339.

Lovett, G.M., Canham, C.D., Arthur, M.A., Weathers, K.C. and Fitzhugh, R.D. (2006) Forest ecosystem responses to exotic pests and pathogens in eastern North America. *BioScience* 56, 395–405.

Marlon, J.R., Bartlein, P.J., Caracillet, C., Gavin, D.G., Harrison, S.P., Higurera, P.E., Joos, F., Power, M.J. and Prentice, I.C. (2008) Climate and human influences on global biomass burning over the past two millennia. *Nature Geosciences* 1, 697–702.

Martin, K.L., Hix, D.M. and Goebel, P.C. (2011) Coupling of vegetation layers and environmental influences in a mature, second-growth Central Hardwood forest landscape. *Forest Ecology and Management* 261, 720–729.

McEwan, R.W., Dyer, J.M. and Pederson, N. (2011) Multiple interacting ecosystem drivers: toward an encompassing hypothesis of oak forest dynamics across eastern North America. *Ecography* 34, 244–256.

McLaughlin, D.L., Kaplan, D.A. and Cohen, M.J. (2013) Managing forests for increased regional water yield in the Southeastern Coastal Plain. *Journal of the American Water Resources Association* 49, 953–965.

McNulty, S., Myers, J.M., Caldwell, P. and Sun, G. (2013) Climate change summary. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Futures Project*. General Technical Report 178. USDA Forest Service, Southern Research Station, Asheville, North Carolina, pp. 27–44.

Meier, W., Bonjour, C., Wuest, A. and Reichert, P. (2003) Modeling the effect of water diversion on the temperature of mountain streams. *Journal of Environmental Engineering – ASCE* 129, 755–764.

Meinzer, F.C., Bond, B.J., Warren, J.M. and Woodruff, D.R. (2005) Does water transport scale universally with tree size? *Functional Ecology* 19, 558–565.

Melvin, M. (2012) National Prescribed Fire Use Survey Report. Technical Report 01-12. National Association of State Foresters and Coalition of Prescribed Fire Councils, Inc. Available at: http://www.stateforesters.org/sites/default/files/publication-documents/2012_National_Prescribed_Fire_Survey.pdf (accessed 14 April 2016).

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Current State and Trends*. Island Press, Washington, DC.

Miller, J.H., Lemke, D. and Coulston, J. (2013) The invasion of southern forests by nonnative plants: current and future occupation, with impacts, management strategies and mitigation approaches. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Futures Project.* General Technical Report 178. USDA Forest Service, Southern Research Station, Asheville, North Carolina, pp. 397–456.

Mitchell, R.J., Youngqiang, L., O'Brien, J.J., Elliott, K.J., Starr, G., Miniat, C.F. and Hiers, J.K. (2014) Future climate and fire interactions in the southeastern region of the United States. *Forest Ecology and Management* 327, 316–326.

Mittman, T., Band, L.E., Hwang, T. and Smith, M.L. (2012) Distributed hydrologic modeling in the suburban landscape: assessing parameter transferability from gauged reference catchments. *Journal of the American Water Resources Association* 48, 546–557.

Naiman, R.J. (2013) Socio-ecological complexity and the restoration of river ecosystems. *Inland Waters* 3, 391–410.

National Research Council, Water Science and Technology Board (2008) *Hydrologic Effects of a Changing Forest Landscape*. National Academies Press, Washington, DC.

Nowacki, G.J. and Abrams, M.D. (2008) The demise of fire and 'mesophication' of forests in the eastern United States. *BioScience* 58, 123–138.

Nowacki, G.J. and Abrams, M.D. (2015) Is climate an important driver of post-European vegetation change in the Eastern United States? *Global Change Biology* 21, 314–334.

O'Gorman, P.A. and Schneider, T. (2009) The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences USA* 106, 14773–14777.

Patterson, L.A., Lutz, B. and Doyle, M.W. (2013) Climate and direct human contributions to changes in mean annual streamflow in the South Atlantic, USA. *Water Resources Research* 49, 7278–7291.

Peterson, J.T. and Kwak, T.J. (1999) Modeling the effects of land use and climate change on riverine smallmouth bass. *Ecological Applications* 9, 1391–1404.

Postel, S. and Richter, B. (2003) *Rivers for Life: Managing Water for People and Nature*. Island Press, Washington, DC.

Riveros-Iregui, D.A., Wang, L. and Wilcox, B. (2011) Ecohydrology and the challenges of the coming decades. *American Geophysical Union, Hydrology Section Newsletter* (July), 32–34.

Rutter, A.J., Morton, A.J. and Robins, P.C. (1975) Predictive model of rainfall interception in forests 2. Generalizations of model and comparison with observations in some coniferous and hardwood stands. *Journal of Applied Ecology* 12, 367–380.

Seastedt, T.R., Hobbs, R.J. and Suding, K.N. (2008) Management of novel ecosystems: are novel approaches required? *Frontiers in Ecology and the Environment* 6, 547–553.

Steffen, W., Crutzen, P.J. and McNeill, J.R. (2007) The Anthropocene: are humans now overwhelming the great forces of nature? *Ambio* 36, 614–621.

Sun, G., Riedel, M. and Jackson, R. (2004) Influences of management of Southern forests on water quantity and quality. In: Rauscher, H.M. and Johnsen, K. (eds) *Southern Forest Sciences: Past, Current, and Future*. General Technical Report SRS-75. USDA Forest Service, Southern Research Station, Asheville, North Carolina.

Sun, G., Caldwell, P.V. and McNulty, S.G. (2015) Modelling the potential role of forest thinning in maintaining water supplied under a changing climate across the conterminous United States. *Hydrological Processes* 29, 5016–5030.

Swank, W.T., Knoepp, J.D., Vose, J.M., Laseter, S.H. and Webster, J.R. (2014) Response and recovery of water yield and timing, stream sediment, abiotic parameters, and stream chemistry following logging. In: Swank, W.T. and Webster, J.R. (eds) *Long-Term Response of a Forest Watershed Ecosystem. Clearcutting in the Southern Appalachians*. Oxford University Press, New York, pp. 36–56.

Swift, L.W. and Baker, S.E. (1973) *Lower Water Temperatures Within a Streamside Buffer Strip*. Research Note SE-193. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina.

Swift, L.W. and Messer, J.B. (1971) Forest cuttings raise temperatures of small streams in Southern Appalachians. *Journal of Soil and Water Conservation* 26, 111–116.

Tague, C.L. and Band, L.E. (2004) RHESSys: Regional Hydro-Ecologic Simulation System – an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions* 8, 1–42.

Tague, C.L., Seaby, L. and Hope, A. (2009) Modeling the eco-hydrologic response of a Mediterranean type ecosystem to the combined impacts of projected climate change and altered fire frequencies. *Climatic Change* 93, 137–155.

Terrando, A.J., Costanza, J., Belyea, C., Dunn, R.R., McKerrow, A. and Collazo, J.A. (2014) The southern megalopolis: using the past to predict the future of urban sprawl in the southeast US. *PLoS One* 9, e102261.

United Nations, Department of Economic and Social Affairs, Population Division (2013) *World Population Prospects: The 2012 Revision, Key Findings and Advance Tables*. Working Paper No. ESA/P/WP.288. United Nations, New York.

United Nations, Department of Economic and Social Affairs, Population Division (2014) *World Urbanization Prospects, The 2014 Revision*. Paper ST/ESA/SER.A/366. United Nations, New York.

Vicente-Serrano, S.M., Camarero, J.J., Zebalza, J., Sanguesa-Barreda, G., Lopez-Moreno, J.I. and Tague, C.L. (2015) Evapotranspiration deficit controls net primary production and growth of silver fir: implications for circum-Mediterranean forests under forecasted warmer and drier conditions. *Agricultural and Forest Meteorology* 206, 45–54.

Vose, J.M., Ford, C.R., Laseter, S.H., Dymond, S.F., Sun, G., Adams, M.B., Sebestyen, S.D., Campbell, J.L., Luce, C., Amatya, D.M., *et al*. (2012) Can forest watershed management mitigate climate change effects on water resources? In: Webb, A.A., Bonell, M., Bren, L., Lane, P.J.N., McGuire, D., Neary, D.J., Nettles, J., Scott, D.F., Stednick, J. and Wang, Y. (eds) *Revisiting Experimental Catchment Studies in Forest Hydrology (Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June–July 2011)*. IAHS Publication No. 353. International Association of Hydrological Sciences, Wallingford, UK, pp. 12–25.

Vose, J.M., Miniat, C.F., Sun, G. and Caldwell, P.V. (2015) Potential implications for expansion of freeze-tolerant Eucalyptus plantations on water resources in the Southern United States. *Forest Science* 61, 509–521.

Wang, L., Liu, J., Sun, G., Wei, X., Liu, S. and Dong, Q. (2012) Water, climate and vegetation: ecohydrology in a changing world. *Hydrology and Earth System Science* 16, 4633–4636.

Ward, E.J., Domec, J.C., Laviner, M.A., Fox, T.R., Sun, G., McNulty, S., King, J. and Noormets, A. (2015) Fertilization intensifies drought stress: water use and stomatal conductance of *Pinus taeda* in a mid-rotation fertilization and throughfall reduction experiment. *Forest Ecology and Management* 355, 72–82.

Wear, D.N. (2013) Forecasts of land uses. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Futures Project*. General Technical Report 178. USDA Forest Service, Southern Research Station, Asheville, North Carolina, pp. 45–72.

Wear, D.N. and Gries, J.G. (eds) (2013) *The Southern Forest Futures Project*. General Technical Report 178. USDA Forest Service, Southern Research Station, Asheville, North Carolina.

Webb, B.W. and Nobilis, F. (1995) Long-term water temperature trends in Austrian rivers. *Hydrological Sciences Journal* 40, 83–96.

Wooldridge, D.D. and Stern, D. (1979) *Relationships of Silvicultural Activities and Thermally Sensitive Forest Streams*. Report DOE 79-5a-5. College of Forest Resources, University of Washington, Seattle, Washington.

Wullschleger, S.D., Hanson P.J. and Todd, D.E. (2001) Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. *Forest Ecology and Management* 143, 205–213.

Yang, Q., Hanqin, T., Friedrichs, M.A.M., Liu, M., Li, X. and Yang, J. (2014) Hydrological responses to climate and land-use changes along the North American east coast: a 110-year historical reconstruction. *Journal of the American Water Resources Association* 51, 47–67.

Zhang, L., Dawes, W.R. and Walker, G.R. (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37, 701–708.