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Review and synthesis

Achievable future conditions as a framework for guiding forest conservation and management

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ABSTRACT

We contend that traditional approaches to forest conservation and management will be inadequate given the predicted scale of social-economic and biophysical changes in the 21st century. New approaches, focused on anticipating and guiding ecological responses to change, are urgently needed to ensure the full value of forest ecosystem services for future generations. These approaches acknowledge that change is inevitable and sometimes irreversible, and that maintenance of ecosystem services depends in part on novel ecosystems, i.e., species combinations with no analog in the past. We propose that ecological responses be evaluated at landscape or regional scales using risk-based approaches to incorporate uncertainty into forest management efforts with subsequent goals for management based on Achievable Future Conditions (AFC). AFCs defined at a landscape or regional scale incorporate advancements in ecosystem management, including adaptive approaches, resilience, and desired future conditions into the context of the Anthropocene. Inherently forward looking, ACFs encompass mitigation and adaptation options to respond to scenarios of projected future biophysical, social-economic, and policy conditions which distribute risk and provide diversity of response to uncertainty. The engagement of science-management-public partnerships is critical to our risk-based approach for defining AFCs. Robust monitoring programs of forest management actions are also crucial to address uncertainty regarding species distributions and ecosystem processes. Development of regional indicators of response will also be essential to evaluate outcomes of management strategies. Our conceptual framework provides a starting point to move toward AFCs for forest management, illustrated with examples from fire and water management in the Southeastern United States. Our model is adaptive, incorporating evaluation and modification as new information becomes available and as social–ecological dynamics change. It expands on established principles of ecosystem management and best management practices (BMPs) and incorporates scenarios of future conditions. It also highlights the potential limits of existing institutional structures for defining AFCs and achieving them. In an uncertain future of rapid change and abrupt, unforeseen transitions, adjustments in management approaches will be necessary and some actions will fail. However, it is increasingly evident that the greatest risk is posed by continuing to implement strategies inconsistent with current understanding of our novel future.

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1. Introduction

The future is increasingly uncertain due to the rapid and compounded environmental, economic, and social changes that characterize the so-called Anthropocene, the geological epoch dominated by human modification of the Earth System (Steffen et al., 2007). High rates of landscape modification and species extinctions are unprecedented, and few, if any, ecosystems remain beyond the influence of human activity (e.g., Likens, 2001; Seastedt et al., 2008; Hobbs et al., 2009). Modern landscapes are social–ecological matrices of patches ranging from "natural/wild" to "intensive commodities-oriented" to "urban" (Hobbs et al., 2014). Novel ecosystems – the product of direct or indirect human activity – are increasingly prevalent and are often characterized by species assemblages and biophysical conditions with no analog in the past (Hobbs et al., 2006). The combined effects of changing climate and land-use, habitat fragmentation, species loss and introductions, and altered nutrient and hydrologic cycles at times exceed the ability of contemporary ecosystems to maintain their structure and function. Such disruptions can result in rapid unanticipated transitions and irreversible thresholds, which have significant social and ecological consequences (see Research Alliance Thresholds Database for examples, http://www.resalliance.org/index.php/thresholds_database). At the same time, there are societal expectations that ecosystems can and will be restored or rehabilitated to functional states, even while climate change, population growth, water diversion, the proliferation of chemicals and numerous other environmental changes impose additional burdens in ways that are not adequately understood (Naiman, 2013). Indeed, a primary goal of ecosystem management is to sustain ecosystem structure and function (Christensen et al., 1996). However, we contend that ongoing changes will in some cases exceed our ability to sustain existing ecosystems, and in such cases, a shift in focus to mitigation and adaptation for ecosystem services will be necessary and therefore produce "novel" ecosystems (e.g., Millar et al., 2007; Hobbs et al., 2014).

The rate and magnitude of environmental and socio-economic change expected over the next several decades will require innovative conservation and management perspectives, as these anthropogenic changes will alter (e.g., increase or decrease) the ability of ecosystems to provide ecosystem services (Hobbs et al., 2014, AIBS, http://actionbioscience.org/environment/esa.html). Ecosystem services are values associated with human well-being and are comprised of needs (i.e., *life sustaining*) and desires (i.e., *quality of life sustaining*), with both tightly tied to ecosystem structure and function. The capacity to maintain or enhance these services is a significant concern, as reductions hold negative and in some cases, potentially dire consequences for human well-being (e.g., www.millenniumassessment.org).

Although many of the concepts presented in this paper can be applied to a wide range of ecosystems, our focus is primarily on forests. Forests are an especially critical component of the modern landscape, providing diverse services such as wood and fiber, climate regulation, carbon storage, biodiversity support, and regulation of water yields and quality (FAO and JRC, 2012; Agrawal et al., 2013; Haddad et al., 2015). Current approaches to forest management in areas dominated by private land ownership are generally fragmented and uncoordinated. While management *goals* may be intended to ensure productivity, environmental quality, and conservation of biodiversity, management *approaches* are often limited in their ability to protect key ecosystem services given the rate and scale of biophysical and social-economic changes. We attribute this deficiency, at least in part, to an outdated view of ecosystems and the Earth System as static or inherently stable rather than dynamic (Pickett et al., 1992; Milly et al., 2008). New approaches focused on anticipating and guiding ecological responses to change are urgently needed to ensure ecosystem services for future generations. This need will likely require challenging some widely accepted principles of forest management and restoration, revising and expanding long-held guidelines and best management practices, and reappraisal of current regulations and laws. For example, focusing conservation efforts on public lands, local preserves, protection of rare species assemblages, and restoration of historic forest ecosystems may prove insufficient. Change is inevitable and might often be irreversible, so the provision of ecosystem services will depend, in part, on the development of novel ecosystems and the emergence of regionally coordinated forest conservation strategies and management approaches that consider both public and private land (Dale et al., 2000; Seastedt et al., 2008; Hobbs et al., 2013; Rieman et al., 2015). Managing in the Anthropocene builds on many of the concepts of ecosystem management (Christensen et al., 1996), but incorporates long-term risk and uncertainty, and recognizes that future biophysical and social-economic conditions constrain desired management outcomes. As a starting point, we propose the following tenets:

1.1. Science-management-public partnerships as a foundation for conservation strategies

It has long been acknowledged that ecological dynamics operate at scales that are independent of ownership and political boundaries, so the effectiveness of conservation strategies will depend on the spatial arrangement of decisions at multiple scales (Christensen et al., 1996). However, this challenge presented by ecosystem management has yet to be resolved. Landscape assessments and management planning that cross these boundaries and incorporate stakeholder concerns and desires may provide the only means of anticipating the cumulative effects of multiple drivers operating at various scales. The emergence of novel ecosystems also creates challenges that span traditional management and technical boundaries (terrestrial, aquatic, game and non-game wildlife, endangered species, etc.), and a need for integrated management across these boundaries.

1.2. A risk-based approach is required to assess current conditions and develop conservation strategies in the face of future uncertainty

It is frequently difficult or impossible to provide rigorously quantified estimates of future uncertainty for decision-making (Carpenter et al., 2009). However, there is increasing certainty that future biophysical conditions will continue to diverge from the past. Further, risks can be quantified by using technical information to develop possible future scenarios (risk assessment) using best available information and accounting for uncertainty. Thus, effective conservation planning and policies must include the envelopes of potential future social-economic and biophysical conditions. We call these envelopes 'Achievable Future Conditions' AFC (see below), and their development moves beyond projections of future biophysical conditions. The AFCs should be designed within the boundaries of social acceptance and capacity for decision-making. AFCs are intended to facilitate social and ecological adaptive capacity to respond to uncertain, even unforeseen, conditions (e.g., Gunderson, 2000; Chapin et al., 2009). Applying a risk-based framework to alternative future scenarios can help identify potential problems and limitations, improving the likelihood that conservation objectives are achievable.

1.3. Achievable future conditions provide the foundation for prioritizing conservation and management actions

The primary objective of the AFC approach is to identify an envelope of *achievable* ecosystem service futures that incorporate current understanding of projected biophysical constraints, social-economic demands, and political realities of land ownership and development. From this foundation, risk management approaches can be used to consider and prioritize management actions that can mitigate undesirable conditions or provide adaptive responses to reduce adverse consequences of anticipated change (Yohe and Leichenko, 2010). Mitigation and adaptation distribute risk and provide diversity of response in the face of uncertainty. The process is inherently iterative, as new information becomes available, strategies for mitigation and adaptation can be revised or reprioritized as needed (Yohe and Leichenko, 2010).

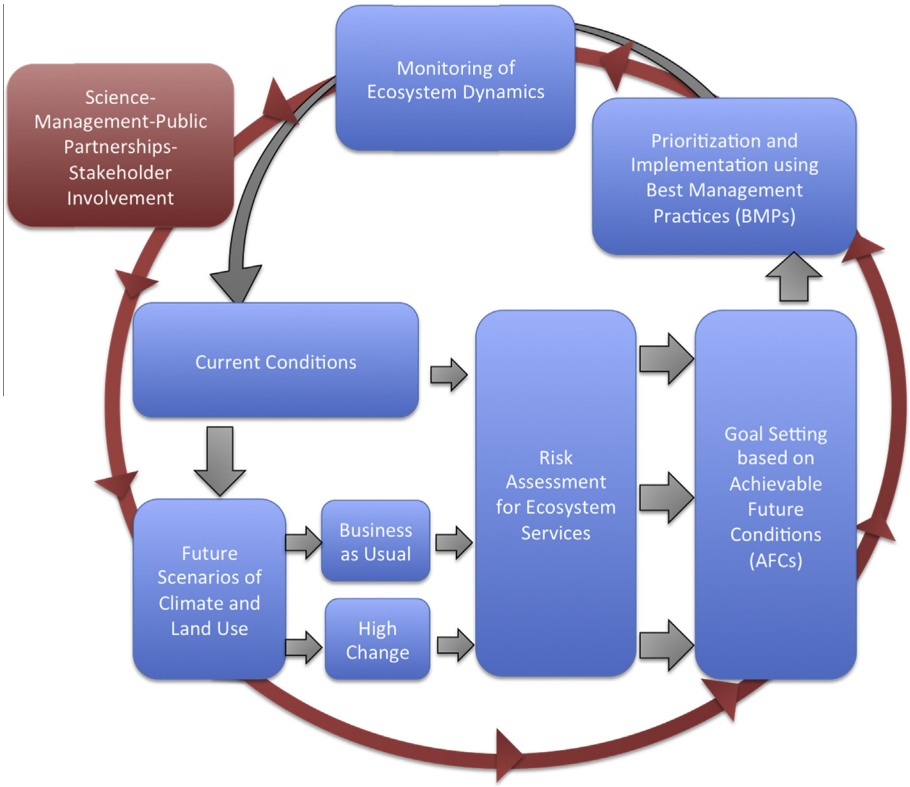

Fig. 1. Framework for conservation management for achievable future conditions, based on scenario and risk assessments. The red line and arrows show that stakeholder engagement is a continuous process, with an expectation of frequent engagement at all stages of conservation management. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We apply a conceptual approach to conservation and management that examines projected environmental changes and ecological responses using the southeastern United States as a template. At the core of our approach is the delineation of AFCs that constrain outcomes within the boundaries set by future biophysical, social-economic and political scenarios. The dominance of diverse private landowners, abundance of forest area and forestry operations, and the dynamics of land uses make the southeastern U.S. challenging and illustrative example.

2. Developing conservation strategies

Our conceptual approach emphasizes that human population growth and development will be rapid, and as a result, biophysical and social-economic systems will continue to change in ways that are uncertain and may result in unprecedented or novel conditions. To ensure that forest ecosystems will continue to provide essential ecosystem services, planning will need to apply risk-based scenarios of future conditions. By necessity these strategies will be forward looking, interdisciplinary, large scale, and include mitigative (actions that reduce vulnerability) and adaptive (actions that cope with consequences) elements. In the following section, we outline critical elements that guide forest responses to rapid environmental and social-economic changes, and provide a conceptual model for the process we propose (Fig. 1). We begin by describing the critical elements required to convert our tenets into effective strategies, provide scenario-based projections for future biophysical and social conditions in the southeastern U.S., discuss the challenges that remain to implement our strategies, and use natural resource management case studies to demonstrate how strategies could be applied to anticipate and manage ecological responses.

2.1. Element 1: Science-management-public partnerships are the foundation for successful conservation strategies

Partnerships between researchers, managers and the public are foundational to identifying priorities for ecosystem services, where meaningful changes and/or scarcities of ecosystem services might arise. Without communication among scientists, managers, and stakeholders at appropriate spatial and temporal scales, the ability to understand ecosystem service tradeoffs will be limited. The ecosystem services that societies depend upon are often not well aligned with political boundaries, so coordination across jurisdictional borders is imperative. Because they are not traded and are by-products of management for other services (i.e., classic production externalities) most ecosystem services are unlikely to be produced at socially-optimal rates.

Stakeholder engagement remains an enormous challenge (e.g., Reed et al., 2009) especially in mixed ownership settings of the Southeast, where the autonomy of landowner choices creates difficulties for coordinating management strategies to achieve regional benefits. Large-scale conservation strategies will be most successful when stakeholders are engaged in developing priorities and understand how risks could be reduced and outcomes for local conditions enhanced through coordinated regional management approaches. Research into the potential benefits and costs of institutional mechanisms, including regulation, or landowner incentives, easements, and trading between landowners and ecosystem service consumers is needed to encourage the coordinated decision-making that can lead to better ecosystem service outcomes. Existing institutions may need to be modified to support coordinated activities within and among constituents to focus on landscape or regional outcomes.

2.2. Element 2: A risk-based approach is required to develop and manage conservation strategies in the face of future uncertainty

There is a growing consensus that future forest dynamics will be altered in ways we will not anticipate, resulting in outcomes that will challenge our understanding (Lindenmayer and Likens, 2010). Beyond ecological dynamics, our understanding of how to guide the responses of coupled social–ecological systems to sustain ecosystem services is a continually evolving area of research (Carpenter et al., 2009). Management planning and evaluation of ecosystem services are predominantly based on current and/or historic conditions, and goals are set to sustain the existing ecosystem structures and functions that support them (Christensen et al., 1996) However, given the pace of climate and land-use changes, historical conditions and ecological communities might become increasingly improbable (e.g., Maes et al., 2012). Current conditions are best viewed as baselines for projecting future scenarios and developing risk management strategies (Fig. 1), but this approach is seldom applied to projections for the provision of ecosystem services at relevant scales (Iverson et al., 2012; Wear and Greis, 2013). The uncertainty of any specific future projection may be high, but a scenario-based approach generates an envelope around the range of possible forest futures (Wear and Greis, 2013) from which risk can be assessed.

Assessing risk can help define outcomes and guide prioritization of potential problems and conservation strategies at large spatial scales. Risk can be described as the product of the frequency of a ‘‘hazardous” event (e.g., drought, storms, wildfire) and the consequences of the event (IPCC, 2014; Yohe and Leichenko, 2010), where ‘‘hazardous” is defined as an event whose frequency or severity is sufficient to cause undesirable outcomes. Characterizing risk requires consideration of the physical, environmental, and socioeconomic factors that determine the ability to resist or recover from a hazardous event, referred to as vulnerability. For example, high severity events (e.g., catastrophic flooding and landslides following extreme rainfall, forest wildfires during droughts) are always high risk, even when the likelihood of occurrence is low. Conversely, low severity events (e.g., tree growth reduction due to short-term drought) generally are low risk, even when the likelihood of occurrence is high. Risk management involves a variety of mitigative and adaptative options that reduce risk or vulnerability to acceptable levels (IPCC, 2007; Yohe and Leichenko, 2010). Examples using this bivariate approach in the ecological literature are rare (Iverson et al., 2012); however, implementing a risk-based framework for management simply requires that assessments are based on projected frequency and estimated consequences (Ojima et al., 2012). The utility of risk-based approaches has been recognized in forest management (e.g., Ojima et al., 2014).

Quantifying risks at fine spatial and temporal scales is likely to be highly uncertain, and in cases where there is insufficient knowledge, it may be necessary to apply qualitative rather than quantitative analyses (e.g., IPCC, 2007; Richter et al., 2011; Melillo et al., 2014). Both quantitative and qualitative information can be used to determine vulnerabilities as well as acceptable levels of risk in response to the changing biophysical and socioeconomic drivers.

2.3. Element 3. Achievable future conditions provide the foundation for prioritizing conservation and management actions

A cornerstone for conservation planning has been the identification of desired future conditions (DFC). Guided by historical endpoints and legal requirements like the Endangered Species Act in the US, DFCs typically include maintenance or restoration to a historical condition of existing species, communities or ecosystems. Although the DFC approach has proven useful, it fails to address how rapidly changing biophysical and social ecological conditions could lead to novel conditions at a landscape or regional scale with unattainable historical endpoints. For example, a DFC for a restored freshwater wetland in coastal areas subject to sea level rise and saltwater intrusion is not feasible (Ardón et al., 2013). Instead, we propose more forward looking DFCs that grant equal or greater weight to projected future scenarios of biophysical and social-economic change (Prato, 2008); more appropriately termed "Achievable Future Conditions" (AFC). Defining AFCs requires a science-management-public partnership to develop social-economic needs and ecological possibilities within the risk-based and scenario building framework. The AFCs along with the identification of vulnerabilities and thresholds for acceptable risk can be used to determine the goals for management.

To be successful at large spatial scales, management actions to achieve AFCs will require widespread acceptance and application. The best analogy is the current implementation of best management practices (BMP) to minimize or mitigate impacts of timber harvesting and site preparation on water quality and site productivity (Prud'homme and Greis, 2002; Aust and Blinn, 2004). We build upon the concept of BMPs, but our discussion extends beyond the current scope and authority of most water-based BMP programs in the Southeast. Our suggestion is that the scope of BMPs should be broadened to include management practices that guide ecological change to attain AFCs. Broadening also implies an ongoing need for monitoring of BMPs (discussed below) for efficacy and the establishment of adaptive mechanisms for adjusting practices to reflect new and anticipated ecosystem conditions (e.g., Westgate et al., 2013). These new BMPs will need to include management options that address suites of ecosystem services and the potential tradeoffs among them, such as regional water yields or climate buffering (Bagley et al., 2014). For BMPs to be effective, they must be consistently implemented at regional scales. Further, it should be noted that while BMPs can be effective for guiding management toward AFCs, some problems may be resolved only through elimination of certain practices altogether, implying a need to structure compensation for landowners, perhaps through a payment/trading system within the relevant landscape.

Determination of BMP effectiveness requires monitoring to assess if desired outcomes are achieved. Hence, continuous monitoring of physical, biological, and social conditions will be critical to ensure that ecosystem service based management goals are attained. Monitoring will also allow approaches to be modified as priorities and evaluations for AFCs shift in response to changing values and/or updated future forecasts. This evaluation process will require substantial investment in "on-the-ground" environmental monitoring (Lindenmayer and Likens, 2010; Fekete et al., 2015). Remote sensing can serve some monitoring needs (Hargrove et al., 2009; Famiglietti et al., 2015), but it has limitations in the types of parameters that can be monitored (Kerr and Ostrovsky, 2003; Pettorelli et al., 2005; Arvor et al., 2013). Existing and emerging networks (e.g., Long Term Ecological Research (LTER), Long Term Agroecosystem Research (LTAR), National Ecological Observatory Network (NEON), Global Lake Ecological Observatory Network (GLEON)), and new remote sensing platforms (e.g., GRACE; Thomas et al., 2014; Reager et al., 2014) may also be useful in meeting some landscape and continental scale monitoring needs (Kao et al., 2012; McDowell, 2015; Schimel and Keller, 2015), but these networks remain largely untested with regards to detecting large scale changes in response to management actions. In addition, emerging networks do not directly address change in forests, particularly on private land. Although not focused on detecting responses to specific management actions, the United Forest Service Forest Inventory and Analysis Program has provided a critical database for assessing changes in forest condition (Woodall et al., 2011). The success of programs such as data on bird populations generated by the Audubon Society's Christmas Bird Count indicate the value of citizen science to meet some of these data needs (Dickinson et al., 2012). Citizen science programs also involve and raise awareness among stakeholders on conservation issues (Aceves-Bueno et al., 2015).

3. The Southeastern template

In this section, we characterize the social and ecological complexity of the Southeastern US and examine future projections for the region as a guide for developing scenario-based management actions. We define the Southeast as the 13 state region included in the Southern Forest Futures Assessment (Wear and Greis, 2013), extending from Virginia and Kentucky, south to Florida and west to Texas and Oklahoma.

3.1. A region of high social and ecological complexity

The Southeastern region is dominated by private land ownership and highly diverse forests, streams, rivers, and wetlands. Forests are the dominant land cover type, exceeding 65% in some states. One third of the private forest lands are under corporate ownership, and these lands are experiencing a rapid shift from ownership and management by integrated forest management companies to real-estate investment trusts (REITs) and timber investment management organizations (TIMOs). This shift toward REITs and TIMOs, which can divest rapidly, makes land ownership and management more difficult to forecast. The remaining two-thirds of the private forest land is owned by individuals or families, who typically lack long-term management plans (Butler and Wear, 2013). Developing and implementing management plans is further challenged by the size of landholdings, with an average family holding of less than 12 ha and trending smaller as land is passed down to multiple heirs (Butler and Wear, 2013).

The abundance of small, private landholdings creates a mosaic of developed areas adjacent to wildlands, with up to 22% of the Southeastern landscape included in wildland–urban interface (WUI) (Zhang et al., 2008). The greatest extent of WUI extends from Virginia to South Carolina, due to development outside mid-sized cities such as Columbia, SC (Zhang et al., 2008, see below). Expansion of WUI causes habitat fragmentation, biodiversity loss, and increases wildfire risk (Radeloff et al., 2005; Haddad et al., 2015).

With an abundance of terrestrial and aquatic habitats, the Southeast is noted for biological richness and high productivity (Burr and Mayden, 1992; Neves et al., 1997; Wear and Greis, 2013), providing diverse ecosystem services (www.teebweb.org). The Southeast leads the nation in timber production, a well-quantified ecosystem service (Wear and Greis, 2013). Payments for other forest-based services, including biodiversity (conservation easements and banks, wildlife viewing, and hunting), carbon offsets, and bundled services (e.g., Wetland Reserve Program that provides multiple services) totaled \$1.7–\$1.9 billion across the US from 2005 to 2007 (Mercer et al., 2011). The greatest payment rates occurred in the Southeast, particularly in Georgia, Florida and Louisiana (Mercer et al., 2011). Incentive programs for water resources are frequently provided to agricultural landowners, but payments for conservation measures or water quality trading programs are difficult to estimate on regional scales (Mercer et al., 2011).

The major river systems in the southeastern U.S. are influenced by multiple landowners and land uses, across diverse political jurisdictions, and have varying stakeholder interests. Municipal, industrial, and power generation are the predominant drivers of water management programs; however, most drinking water in

Table 1
Organizations currently working at landscape scale management coordination in the Southeast. These organizations can be key players in any new efforts in conservation management; however, a key distinction between existing efforts and the proposed framework is the focus on scenario-based planning, risk assessment, and landscape monitoring.

Organization	• Description • Goal • Guiding documents	• Public–private partnerships • Ownership focus	• Scenario-based future planning, risk assessment, or landscape monitoring?
Landscape Conservation Cooperatives (LCCs)	• Collaboration among FWS, USGS, state agencies. • Support integrated landscape conservation. • Spatially explicit Conservation Blueprint	• Yes • Primarily focused on public land	• Capacity to update conservation blueprint
Coalition of Prescribed Fire Councils	• Promotes prescribed fire management, supports landowners.	• Yes- • Primarily focused on private land	• No
America's Longleaf Initiative	• Federal, state and private industry collaboration across nine Southeastern states • Goal to more than double the area of longleaf pine in 15 years	• Yes • Focused across ownerships	• Local implementation teams
Greater Okefenokee Association of Landowners (GOAL	• Federal, state and private industry landowners in the Okefenokee region of GA, FL • Goal to respond to wildfire and reduce risk.	• Yes	• No
Flint Riverkeeper	• Stakeholder NGO • Goal to "restore and preserve the habitat, water quality and flow of the Flint River for the benefit of current and future generations and dependent wildlife"	• Yes	• No
ACF Stakeholders	• Stakeholder NGO • Goal to "achieve equitable water-sharing solutions among stakeholders that balance economic, ecological and social values, while ensuring sustainability for current and future generations"	• Yes	• No

the Southeast U.S. is derived from surface water sources (Caldwell et al., 2014). Water quality guidelines for large rivers are set through federal regulation and administered by states (i.e., Clean Water Act and NPDS permitting). Adjacent land use has a large effect on patterns of runoff and water quality. Non-point source runoff is often unregulated on private lands and Best Management Practices (BMP's) are voluntary and not always implemented, particularly for smaller streams (Shortle and Horan, 2013). Thus, individual landowner management decisions can have a large effect on runoff into stream reaches crossing the landowner's property. Many larger rivers in the Southeast are regulated by impoundments, whose operating authority and procedures are under control of the US Army Corps of Engineers or other agencies (Benke, 1990).

There is very little practical coordination of management actions at regional scales in the Southeast, despite the objective of "all lands" management approaches by some agencies and conservation groups (Table 1). Notable exceptions include a relatively new effort at range-wide restoration of longleaf pine. Current conservation and knowledge transfer programs are developed and implemented by organizations operating at different scales, sometimes with contrasting objectives and guiding principles. For example, public land management plans emphasize a spectrum of goals, from a broad complement of multiple uses (e.g., National Forests, US Forest Service (USFS)) to long-term protection (e.g., US National Park Service, or Wilderness Areas). Management plans for large private landowners (e.g., The Nature Conservancy, forest industry, land trusts, hunting preserves) typically focus on a narrower set of goals specific to institutional objectives. Goals and objectives may be narrower still for small non-industrial private forest landowners. Communication and knowledge transfer in the Southeast derives from a culture of independence and a strong southeastern legacy of private property rights, therefore, is often site-specific and based on local experience. This situation suggests that private landowner participation in coordinated, large-scale conservation efforts is a key challenge requiring innovative strategies to incentivize engagement (Wear and Greis, 2013).

3.2. Scenarios for the future

Projections for the Southeast indicate a future climate that is hotter with more variable precipitation (IPCC, 2014). Although precipitation projections are uncertain, greater evaporative loss from increased temperatures is expected to increase water stress (Liu et al., 2013a; Lockaby et al., 2013). The growing human population will rely on an increasingly urbanized landscape for ecosystem services, suggesting the risk of ecosystem service losses or disruptions is increasing (Wear and Greis, 2013). Climate models project steady warming across the region, though at varying rates and with subregional differences (IPCC, 2007; McNulty et al., 2013). Temperatures are projected to increase between 0.5 and >3.5 °C over the next 50 years, with greater increases in the western part of the region. Precipitation projections vary across models, suggesting potentially high uncertainty. As the climate changes, estimates indicate rapid land use-land cover (LULC) changes due to increasing population, with 12–17 million ha of new development by 2060 (Wear and Greis, 2013). Projected loss of rural land ranges from 4 to 9 million ha (6.5–13.1%) for forest, and 2–7 million ha (6–19%) for agriculture. Development and population growth are expected to be greatest at the periphery of urban centers, particularly in the Piedmont of the Southern Appalachian Mountains from Raleigh NC to Atlanta GA, and along the Atlantic and Gulf of Mexico coastal zones (Fig. 2, Wear and Greis, 2013; Terando et al., 2014). Scenarios with high economic growth result in more urbanization spread across a larger area (Fig. 2). Increasing urban populations are correlated with increasing real incomes; however, the economic conditions in depopulating rural areas are likely to decline, increasing the vulnerability of rural communities to extreme events and reduction of ecological services (Gaither et al., 2011). Differences in economic position and general perspectives on land use (rural-utilitarian vs. urban-esthetic as an example) suggest both economic and political tensions between stakeholders in contrasting segments of the Southeastern landscape.

Projections of forested LULC in the Southeast depend on population- and income-growth drivers as well as agricultural

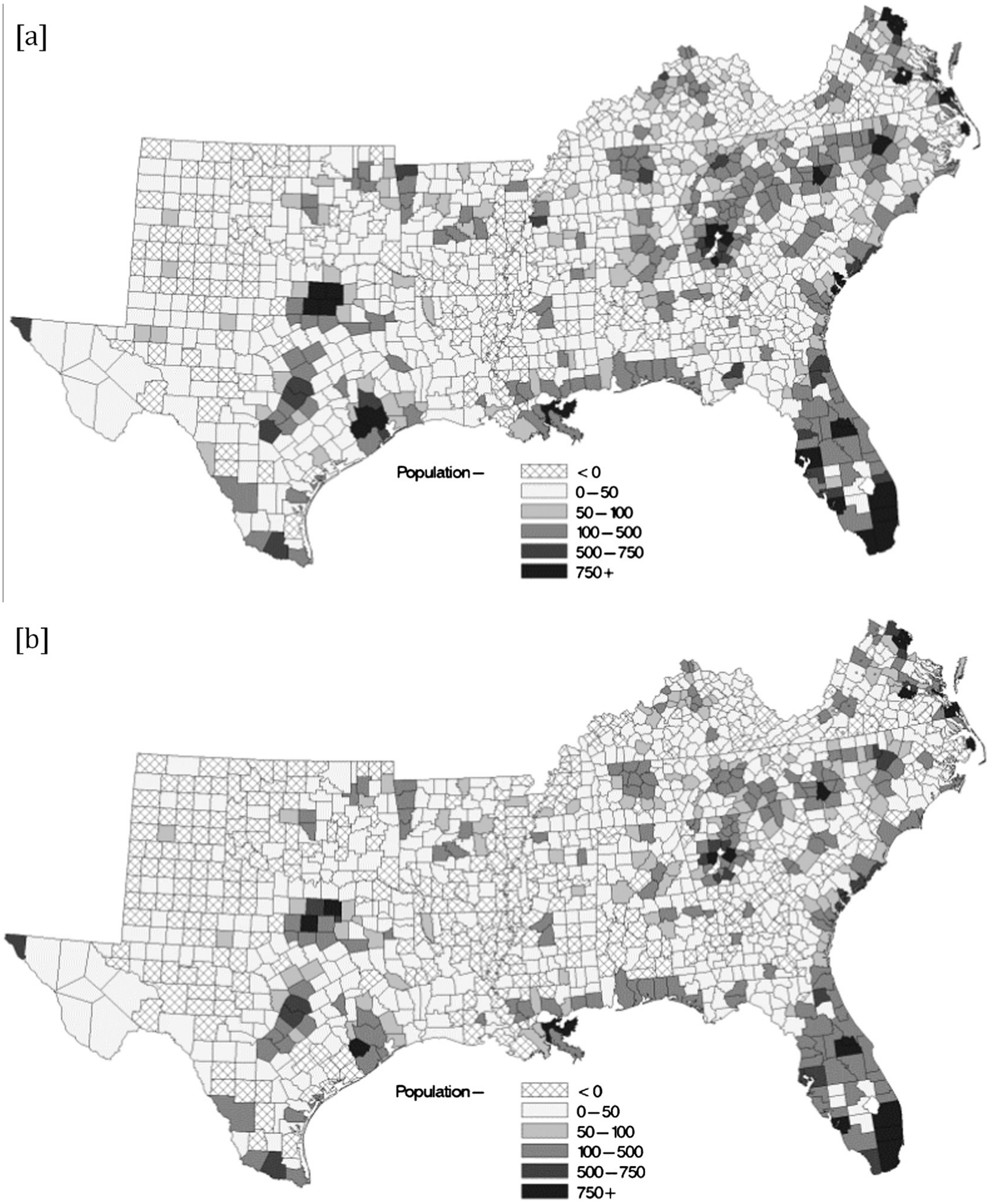

Fig. 2. Projection of population change in the Southeastern United States, 2010–2060, assuming the (a) A1B storyline of low population growth, high economic growth, high-energy use; and (b) B2 storyline of moderate growth and energy use from the 2010 Resources Planning Act (RPA) assessment. Note that counties in crosshatch have forecasted population losses. Adapted from Wear and Greis (2013).

and timber prices. Until recently, forest losses associated with development were offset by afforestation of marginal agricultural land. Recent projections indicate agricultural LULC will stabilize or even increase due to strong future agricultural markets (Wear and Greis, 2013). Forest losses are projected to be greatest from northern Georgia through North Carolina and into parts of Virginia (Fig. 3). Other areas of projected concentrated forest loss are the Atlantic Coast, along the Gulf of Mexico, and outside of Houston, TX. Forest type is particularly responsive to market conditions, with projections indicating an increasing trend in planted pines that began in the 1950s (Wear and Greis, 2013). Planted pines currently occupy almost 16 million ha, or 19% of the 83 million ha of forest in the Southeast (Wear and Greis, 2013; Klepzig et al., 2014). Projections of urbanization and timber prices suggest that by 2060, planted pines could increase by 11.3–27.3 million ha (34% of forest area), replacing much of the remaining natural (non-plantation) pine forest (Wear and Greis, 2013).

Scenarios of future climate and land use suggest forest conservation and management challenges will increase in the Southeast (Wear and Greis, 2013). The region faces a future of increasing fragmentation, loss of deciduous forest area in the Piedmont and Southern Appalachians, and potential conversion of natural forest to pine plantations in the Coastal Plain. These changes create uncertainty for important ecosystem services including biodiversity conservation, maintenance of hydrologic function, carbon sequestration, and climate buffering (Wear and Greis, 2013). Responding to change will require new thinking and strategies. For example, future forests may be subject to large-scale severe

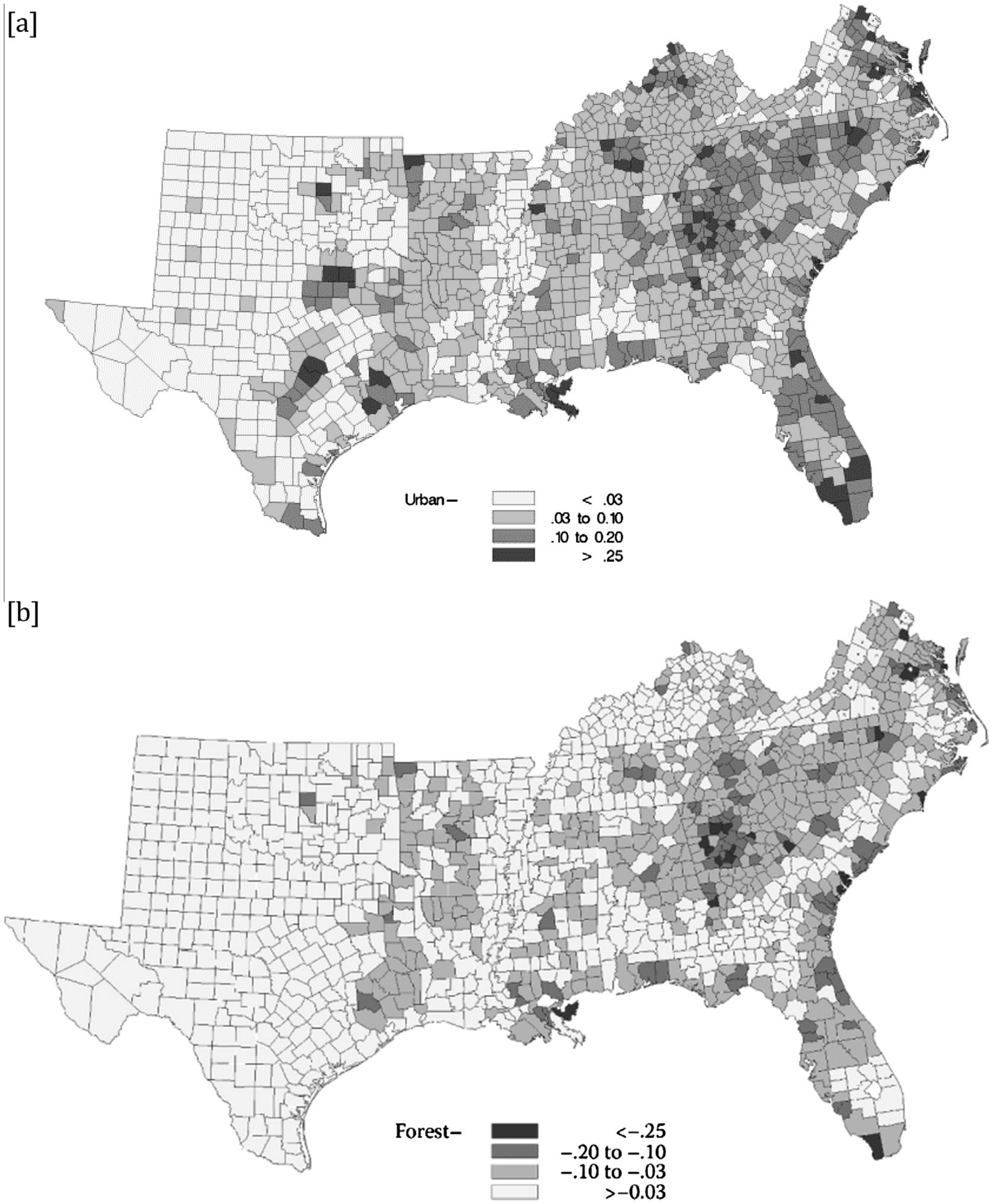

Fig. 3. Proportional change in land 1997–2060. (a) Percent change (increase) in urban land use. (b) Percent change (decrease) in forest land use. Adapted from Wear and Greis (2013).

wildfires, which have not been a primary concern in the past due to management including prescribed fire (Melvin, 2012). Predicted hotter conditions and thus, increased Keetch-Byram Drought Index (KBDI) seem likely to increase wildfire risk (Liu et al., 2013a, Fig. 4), causing concerns for the safety and health of an expanding population of the WUI and in depopulating rural areas. The confluence of population growth, urbanization, climate change, and loss/fragmentation of forests will also increase the water supply stress (water demand/water supply) between 10% and 100% throughout much of the Southeast (Fig. 5).

4. Applying the framework to conservation challenges in the Southeast US

In the following section, we use case studies focused on wildfire risk and water scarcity to explore how our framework could be used to develop and attain AFCs in a real-world setting. Characterizing current conditions is a logical starting point for the process. In the examples that follow, regional drought conditions caused undesirable events (wildfires and exceptionally low stream flows). These observed events, along with climate, land use, and population projections, have created concerns about future risk and exposed vulnerabilities to both stakeholder and management communities. We discuss these case studies in the context of our conceptual model and framework, not to criticize past efforts, but to show how regional conservation strategies and actions might be enhanced to address these concerns.

5. Fire management and the Georgia Bay Complex wildfires

The Southeast experiences more wildfire than any other region of the country, averaging 45,000 fires a year over the six year

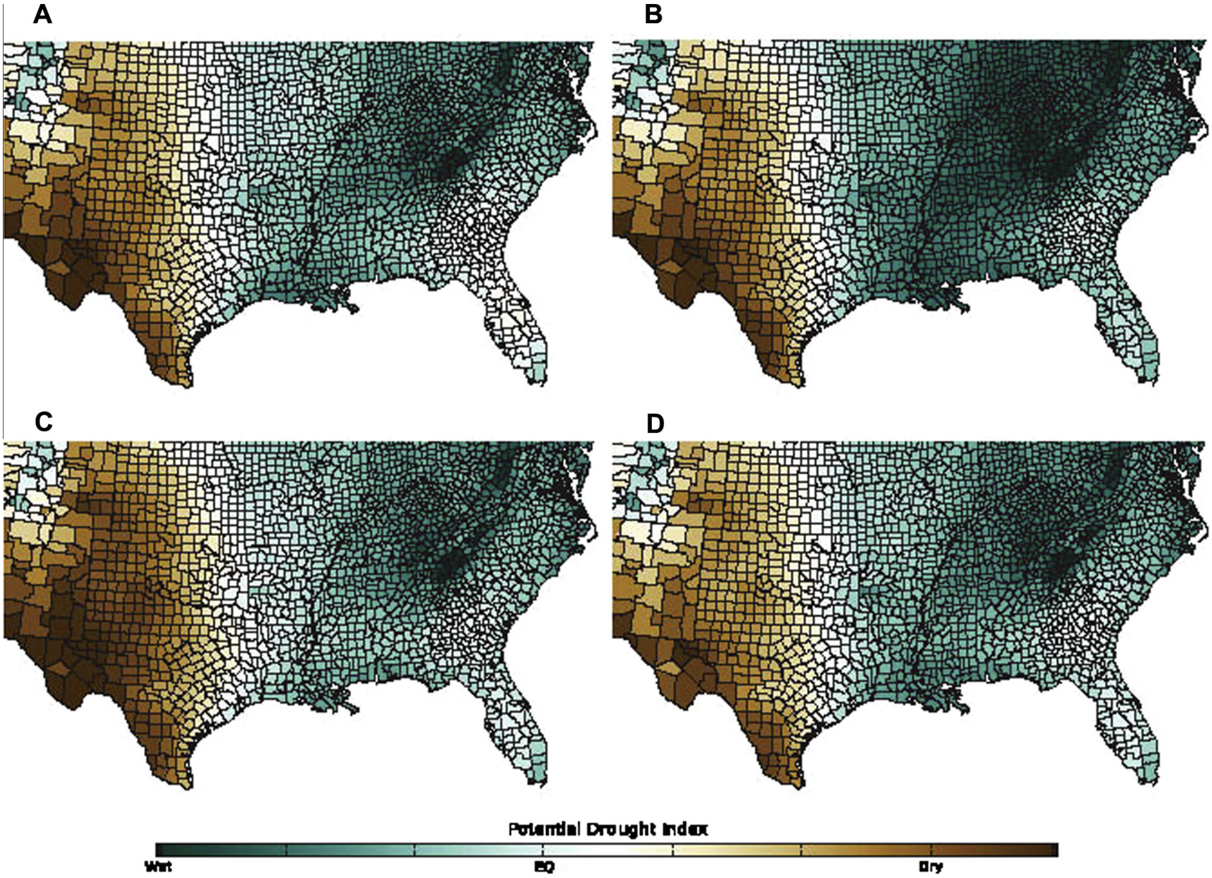

Fig. 4. Comparison of annual fire potential for future conditions (2060). Adapted from Stanturf and Goodrick (2013).

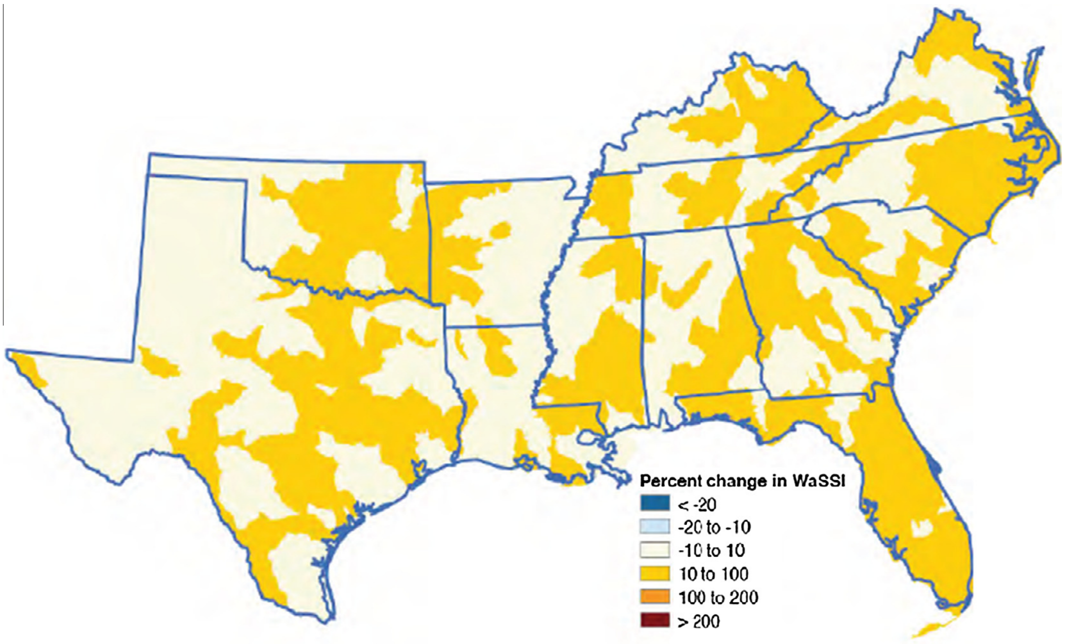

Fig. 5. Water supply stress index as identified by the Water Supply Stress Index (WaSSI) and calculated as the ratio of total demand and total water supply. Values represent change in 2050 from current conditions, based on population projections. Adapted from Wear and Greis (2013).

period from 1997 to 2003 (Mitchell et al., 2014). Typically, wildfires are not severe or large, as many Southeastern ecosystems are adapted to short fire return intervals that reduce fuel loads (Liu et al., 2013a). The Southeast also has a strong tradition of prescribed fire management, implementing more burns than other regions combined (Melvin, 2012). Prescribed burns have

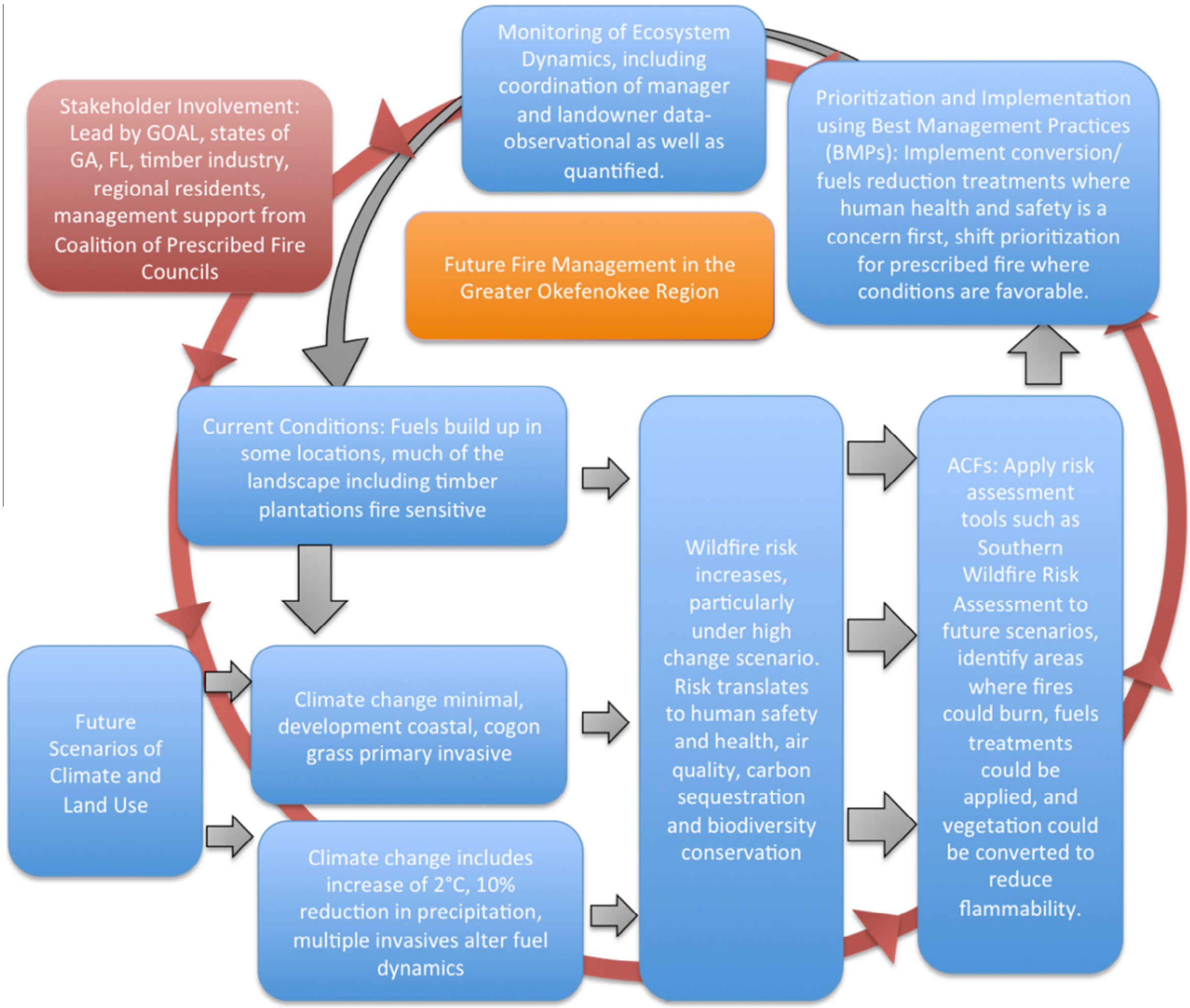

Fig. 6. Application of conservation framework to fire management in the Okefenokee region of Georgia and Florida. Increasingly quantitative data could be incorporated as it becomes available.

historically been implemented for management of fire-dependent biodiversity, including game species. Despite regular fuels management, Southeastern wildfires destroy more structures than in other regions and can lead to substantial timber losses for affected landowners (Stanturf and Goodrick, 2013). Projections for climate and land use in the Southeast indicate wildfires will be more frequent, intense, and occur over a fire season that will be extended by 1–3 months (Liu et al., 2013a, 2013b). These conditions suggest that wildfires will burn under more extreme conditions and fire frequency will increase in ecosystems with longer fire return intervals, including wetlands that historically burn only during significant droughts (Stanturf and Goodrick, 2013). The risk imposed by future wildfire will be compounded because of projected expansion of WUI and dispersed rural housing (Gaither et al., 2011; Liu et al., 2013a; Zhang et al., 2013). As wildfire risk increases, fuel management will be constrained because fewer days will meet criteria for prescribed fire implementation (Liu et al., 2013a; Mitchell et al., 2014). Recent wildfires in Georgia and Florida provide useful guidelines for potential future wildfire in the Southeastern U.S., and we use the Greater Okefenokee region as an application of our risk-based management framework (Fig. 6).

In 2007, the Georgia Bay Complex Fires (including the Sweat Farm Road Fire, Big Turnaround Fire Complex and the Bugaboo Scrub Fire) burned 242,800 ha across federal, state and private lands under severe drought conditions. The fires exhibited novel, erratic fire behavior, including flame lengths as high as 30 m (Edwards et al., 2013). Timber losses on private lands were in excess of $58 million (Mitchell et al., 2014). Smoke from the fires degraded air quality from Mississippi to North Carolina (Odman et al., 2007; Mitchell et al., 2014) and caused the temporary closure of two interstate highways in southern Georgia and northern Florida (I-10 and I-75) (Edwards et al., 2013). Adjacent communities were at particularly high risk, as many of them had been identified as economically vulnerable (Gaither et al., 2011). Only four years later, the 2011 Honey Prairie Complex Fire became the second largest in the Okefenokee region's history (125,129 ha) (http://www.fws.gov/okefenokee/HoneyPrairieArchive.html). The estimated historic return interval for such large fires was approximately 150 years (Yin, 1993).

5.1. Science-management-public partnerships as a foundation for conservation strategies

Collaboration and coordination are particularly critical for fire management in the Southeast because of fragmented land ownership, high WUI, economically vulnerable rural residents, and valuable, fire-sensitive timber resources. The Greater Okefenokee Association of Landowners (GOAL) was formed between US Fish and Wildlife Service, state agencies from Georgia and Florida, and private landowners to coordinate fire responses, motivated by an active wildfire season in 1994 (Table 1). While it includes representatives from adjacent rural communities, GOAL would need to expand to facilitate wildfire mitigation for socio-economically vulnerable rural residents, including renters and their properties, to mitigate wildfire risk (Gaither et al., 2011). Further, GOAL does not currently include significant participation from the scientific research community, which could facilitate estimates of future fire risk, and move the organization toward more anticipatory strategies.

5.2. A risk-based approach to assess current conditions and develop conservation strategies in the face of future uncertainty

Risk assessment and prioritization are key goals of the Stewardship and Fireshed Assessment (SFA) process, which is increasingly implemented on public lands in the West (Bahro et al., 2007). The SFA uses a collaborative approach incorporating expert opinion, stakeholder involvement, and simulation modeling of management outcomes to prioritize landscape-scale wildfire risk reduction (Bahro et al., 2007). Landscapes are delineated into firesheds, usually several times the spatial extent of large, severe wildfires (Bahro et al., 2007; North et al., 2012). Delineations are based on historic fire data, fuels, LULC including WUI, expert opinion and stakeholder involvement. Coordinated strategies for fire and fuels management are developed and implemented using firesheds as management units (Bahro et al., 2007; North et al., 2012).

Application of fireshed management concepts in our conservation and management framework (Fig. 6) begins with a fuels assessment to establish baseline risk conditions. The Southern Wildfire Risk Assessment Tool is a potentially important resource to establish baseline conditions (www.southernwildfirerisk.com) that the scientific community could add to as a resource for GOAL. The current map indicates that the Okefenokee fireshed includes areas of moderate and high severity fire risk, primarily in the uplands. Established baselines can then be incorporated into future scenarios to determine the impacts of projected changes in climate and LULC. For example, the fire season in the Okefenokee region is expected to extend two months longer into the autumn by 2060 (Liu et al., 2013a), potentially increasing the intensity and thus severity of fire. This kind of future scenario projection is a key contribution science partners could provide to GOAL. Even if detailed assessments of future fire risk were to prove difficult to project, scenario based planning could use an experimental approach to test the robustness of management planning. For example, if fuel moisture were reduced by 10% across the fireshed, would it be important to consider revisions or shifts in areas at high risk?

Fire management in forests also will be challenged by increasingly fragmented landscapes with shifting and novel species compositions. Given that Jacksonville, FL is a major port and the center of urban development in the Okefenokee region, commercial transport and fragmentation from development will likely facilitate the spread of invasive species (Wear, 2013). The expansion of invasive species will alter fuel dynamics and in turn, fire behavior. Climatic envelope mapping can inform potential invasive species spread across regional scales for inclusion in potential fuels mapping (Sheppard et al., 2014). Using this approach, Bradley et al. (2010) indicate ongoing range expansion of cogongrass (*Imperata cylindrica*), which is highly flammable. Mapping potential scenarios of fuels will be a necessary part of fireshed risk mapping. This mapping could include both continuous updating of invasive occurrence and abundance from monitoring programs that might include a citizen science component, as well as more technical species occurrence projections provided by scientific partners.

5.3. Achievable future conditions provide the foundation for prioritizing conservation and management actions

In the context of fire management, current strategies that could be thought of as AFC-based BMPs include "Fire-wise" community guidelines (www.firewise.org), which provide recommendations for landowners to reduce impacts and spread of wildfires, such as using less flammable landscaping and building materials (Stephens et al., 2013). Such programs historically emphasized fire on a short term and case-by-case basis according to the landowner and community resources. Expanding BMPs to firesheds and incorporating preventative approaches that account for future climate and land use change would broaden protection of human health, safety, and economic interests across the Southeast, while maintaining biodiversity in fire-dependent communities (e.g. Gaither et al., 2011; Stanturf and Goodrick, 2013; Mitchell et al., 2014).

In firesheds where the risk and potential costs of wildfire are increasing, BMPs could guide the determination of acceptable levels of risk and effective management responses. Within such risked-based approaches, high severity crown fire might be acceptable where human health and safety are not jeopardized, such as across interior wilderness areas of Okefenokee NWR. This approach is consistent with fireshed management, where severe wildfires are allowed to burn in certain parts of the landscape to protect other areas (e.g., North et al., 2012; Stephens et al., 2013). Prioritizing areas of risk, including potential fire spread across the landscape will require mapping not only future biophysical conditions (including drought stress and fuel loads) but also social-economic conditions from future WUI and economically vulnerable areas (e.g. Gaither et al., 2011). Establishing priorities will require technical guidance from scientists in collaboration with land managers and owners. In high-risk areas of firesheds such as WUI areas, recommended BMPs might include physical fire breaks (Agee et al., 2000) or establishment of novel vegetation communities with lower fuel loads and flammability. Recommendations might also mean that traditional Southeastern landscaping with flammable materials, such as pine straw, will need to be reevaluated and/or moved away from structures. Landowners who wish to reduce the risk to timber investments might consider planting fire-resistant and resilient species such as longleaf pine (*Pinus palustris*) in place of loblolly (*Pinus taeda*) or slash pine (*Pinus elliotti*) and designing pine plantations to minimize risks to developed areas (Mitchell et al., 2014). These types of management approaches are unlikely to be perfectly aligned with the interests of landowners – for example, fire breaks may only provide benefits to adjacent areas – so they probably would not be adopted without some type of compensatory exchange between landowners and beneficiaries, or policy intervention, most likely at the state level.

Prescribed fire, along with wildland fire acceptance, or allowing wildfires in wilderness areas to burn, will continue to be important BMPs for wildfire and biodiversity management in the Southeast (Kirkman et al., 2001; Melvin, 2012; Stanturf and Goodrick, 2013; Mitchell et al., 2014). Prescribed fire is often viewed as the most cost effective and ecologically beneficial fuels management strategy (Melvin, 2012). However, managers should expect that opportunities to use fire would occur less frequently under future conditions, because of altered climate and concerns about smoke management and air quality (Bhoi et al., 2009; Mitchell et al., 2014). Public acceptance of prescribed fire will also be necessary, and outreach from scientists and managers can provide the public with information as a key part of the decision making process as to where and when prescribed fire will be acceptable. Further, it will not be sufficient to reduce fire risk on public land alone. Scientists and managers can provide private landowners with information and technical support to implement prescribed burning. Already, states including Georgia and Florida provide assistance to landowners who seek it; however, states might need to move to a more proactive recruitment process as wildfire risk increases.

Where prescribed fire is not feasible, implementation of firebreaks and/or conversion to less flammable vegetation, particularly in the WUI, will be important BMPs to reduce future wildfire risk across property boundaries. Even with aggressive management of fuels, many areas are likely to experience high severity fires that may substantially alter ecosystem structure and function. During the Georgia Bay Complex Fires, some recently prescribed burned (<5 years) stands in the Osceola National Forest experienced high severity burns due to extremely dry weather and high-risk fire conditions (Fire Behavior Assessment Team 2007). Further, GOAL sought to create a wildfire buffer around the Okefenokee (goalpartners.org) following the 2007 fire season; so, the spread of the 2011 fires suggests that management will need adaptive and increasingly aggressive approaches to contain fire under projected warmer and drier climatic conditions (Stanturf and Goodrick, 2013).

For the Okefenokee fireshed, determining acceptable levels of risk for management prioritization will require coordination among state and federal agencies, GOAL, Prescribed Fire Councils, and private landowners. Additional collaboration with climate and fire scientists will be required to provide the technical information necessary to support informed risk assessment and decision making. Risk assessment will most likely include multiple priorities and therefore tradeoffs across the fireshed. Public agencies will likely prioritize risks to human health and safety, whereas private landowners might prioritize protecting high-value timber resources. Such conflicting priorities could increase the overall fireshed risk. What is needed is an institutional structure to incorporate scenario-based forecasts across ownership boundaries within firesheds, to establish consensus-based goals for managing fire risk at a landscape scale, and regulatory or compensatory mechanisms for facilitating private management activities that support broader social benefits.

6. Water resources in the Flint River Basin

Human population growth, urbanization, and climate change are increasing regional water demands and depleting water sources in many areas of the Southeast (Sun et al., 2008; Carlisle et al., 2011; Rugel et al., 2012; Famiglietti and Rodell, 2013). The ability of water resources to meet higher demand is limited, as the Southeast is characterized by small river basins, modest groundwater resources, and relatively small, shallow storage reservoirs that are designed primarily for flood control (Sun et al., 2013). In areas of high population growth such as the Piedmont, which includes Atlanta GA, Charlotte NC, and Raleigh-Durham NC, regional heat-island effects (e.g., www.epa.gov/heatisland/) formed by the combination of rapid urban/suburban expansion and climate change may further stress water resources (Terando et al., 2014). Increased municipal water demands will affect aquatic biodiversity, as the development of water resources is associated with a decrease in faunal richness and regional homogenization of fauna (e.g., Moyle and Mount, 2007).

We use the Flint River in Georgia to illustrate how our risk-based conservation framework could address water resource and aquatic biodiversity conservation concerns in the region. Draining over two million ha, the Flint River watershed is approximately 50% forested, 40% agriculture, and 5% urban. Hence, the region is a matrix of mixed land uses that interact in complex ways. Originating in the metro Atlanta area, the Flint flows southward across the Piedmont and Coastal Plain to its confluence with the Chattahoochee River, forming the Apalachicola River, which flows from southwestern Georgia to the Florida panhandle. Water is withdrawn primarily for power generation and municipal supply in the upper basin near Atlanta, and for agricultural irrigation (e.g., row crops, pecan orchards) in the lower portions of the basin. Water use has been expanding rapidly throughout the basin since the 1970s and growing season stream flows are declining, particularly during droughts (Rugel et al., 2012; Emanuel and Rogers, 2012). During this period, there was no significant trend in annual or seasonal precipitation (Rugel et al., 2012; Emanuel and Rogers, 2012). Between 2010 and 2050, the population of the upper basin is expected to increase 63%. In the lower Flint, water demand increased rapidly with the adoption and expansion of crop irrigation during the 1970s and 80s (Couch et al., 1996). Total water use in the Flint River Basin is projected to increase from 4.3 million m^3 per day (Mm^3 D) in 2010 to 4.9 Mm^3 D in 2050 (Lower Flint Ochlockonee Watershed Council, 2011; Upper Flint Watershed Council, 2011). With a future of increasing population, land use changes, temperatures, and uncertain precipitation, water resource issues will become more critical. Allocation of water from the Apalachicola–Chattahoochee–Flint River Basin has been a long-term source of contention between Georgia, Florida and Alabama (see acfstakeholders.org). However, the development of water management guidelines for the Flint River, and many other southeastern rivers, is hindered by the lack of systematic assessment of hydrologic change across mixed land uses. Particularly lacking is information about changes in water yield or water balance in watersheds undergoing development or land conversion (e.g., Sun et al., 2008). Information concerning biological responses, essential for developing water management guidelines, is also not well developed for southeastern rivers. In the following sections, we explore the use of our conservation framework to address water resource issues in the Flint basin (Fig. 7).

6.1. Science-management-public partnerships as a foundation for conservation strategies

Stakeholder concerns about the availability of clean, fresh water in the Flint River basin led to the formation of the Flint Riverkeeper (FRK) in 2008 (flintriverkeeper.org). Major stakeholders within the basin include municipalities, agriculture, canoe liveries, and anglers. Concern arose from an apparent increase in frequency and duration of droughts and an increase in the frequency and duration of extreme low flows. Collectively, those observations suggested that the ability to meet water demands, recreational needs, and support instream biota were increasingly uncertain (Emanuel and Rogers, 2012). There was also recognition that addressing water resource problems in the Flint River required a broad integrative approach and coordinated efforts among diverse stakeholder interests.

6.2. A risk-based approach to assess current conditions and develop conservation strategies in the face of future uncertainty

Future water resources and aquatic biodiversity depend on sustained streamflow, but this requirement encompasses the magnitude, duration, frequency, timing, and rate of change in both common and uncommon events (i.e., low flows, base flows, and flood pulses) (Olden and Poff, 2003; Poff et al., 2010). Characterizing flow alteration is difficult because of the complex nature of the hydrologic regimes and because information concerning biotic responses to altered stream flows is site specific and/or often lacking. The Sustainable Boundary Approach (SBA) is a method of stream flow assessment that simplifies data needs and reduces complexity. Using a combination of stakeholder consensus, expert-opinion and evidence, an acceptable range of daily stream flow is developed based on historical records (Richter, 2009). This approach incorporates societal values, technical expertise, along with flow augmentation and reduction, in water management planning. The SBA approach has been further refined with the

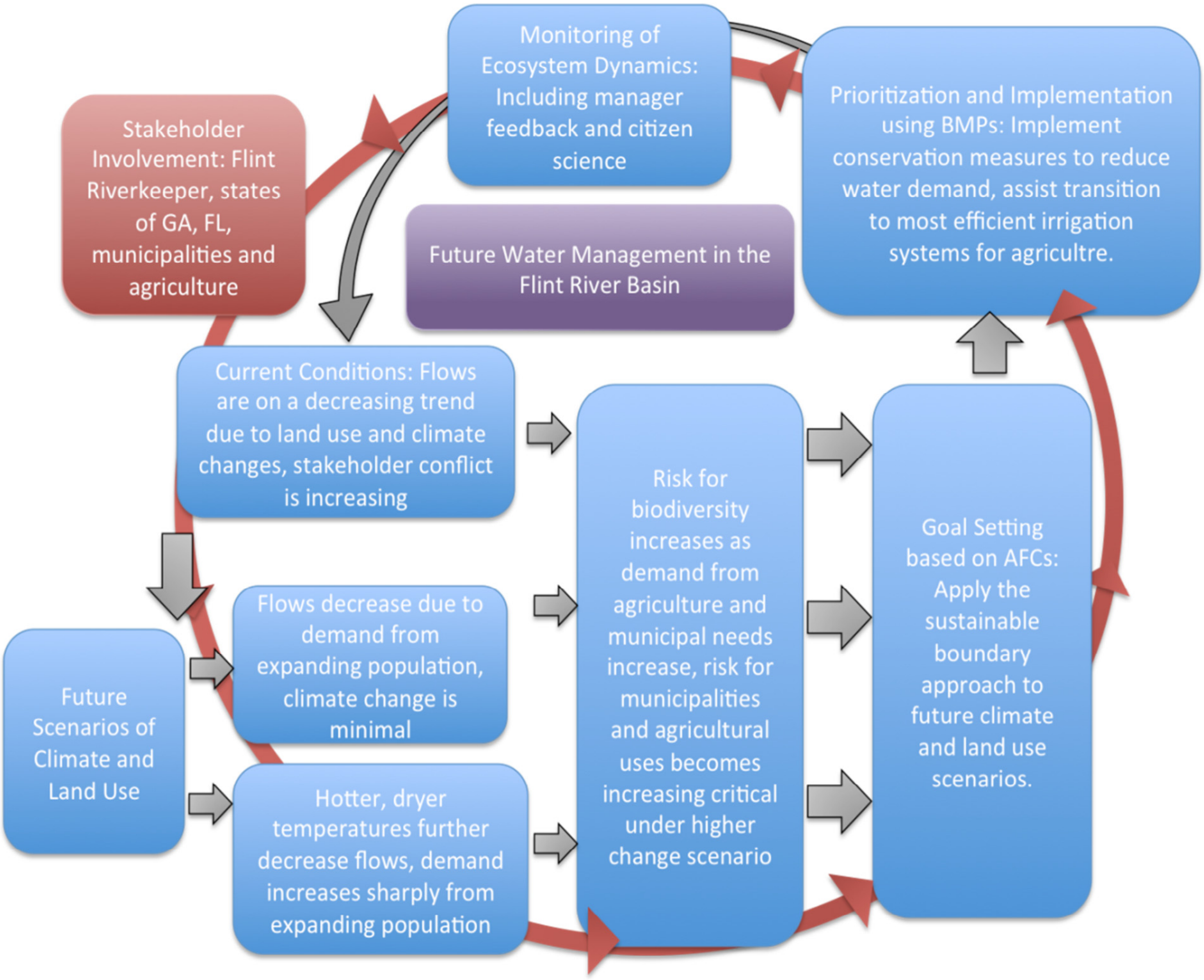

Fig. 7. Application of conservation framework to the Flint River watershed in Georgia.

introduction of a ‘presumptive standard’ for environmental flow protection (Richter et al., 2011). Presumptive standards are risk-based guidelines using case studies and real world experience with the SBA template as a conceptual model.

We used the SBA and Presumptive Standard approach to assess hydrologic alteration and develop AFCs for water resources in the Flint River (Richter et al., 2011). The main stem of the Flint River has a number of US Geological Survey (USGS) gauging stations that provided data (i.e., daily flow) for the SBA analysis. Based on demographic and land use data, we used 1975 as a breakpoint for pre- and post-hydrologic alteration (e.g., Rugel et al., 2012; Emanuel and Rogers, 2012); i.e., data from WY 1940–1974 were used to estimate ‘pre-alteration’ conditions, and data from 1975 to 2012 represented ‘altered’ flows. We calculated median average daily flow for each day of the year, and upper and lower boundaries for SBA were calculated as the median daily flow ±20% (i.e., presumptive standard; Richter et al., 2011).

Median daily flow for the altered flow period shows substantial departure from the pre-alteration period (Fig. 8). From April through mid-October for WY 1974–2012, median daily flows are often at or below the lower SBA boundary. Even during winter, when the WY 1974–2012 flow generally resided within the SBA band, median daily flow seldom equaled or exceeded the pre-alteration median value. This analysis suggests that substantial hydrologic alteration has already occurred in the Flint River and is reflected in lower flows, particularly during late spring and summer.

Under climate change scenarios, warmer temperatures, along with variable rainfall, will result in a continuing trend of hydrologic alteration. Human population growth would create additional stress on water resources, exacerbating climate effects. Reduced summer stream flow and increased stream temperature have negative implications for ecological communities in the river, such as freshwater mussels (Golladay et al., 2004; Emanuel and Rogers, 2012), native crayfish (Sargent et al., 2011), and fish (van den Avyle and Evans, 1990; Freeman et al., 2012; Emanuel and Rogers, 2012). In addition to ecological effects, low flows would reduce the seasonal volume of water available to receive permitted discharges. Increased discharge concentration, along with ecological changes may alter river assimilative capacity and increase water treatment costs for downstream users.

The range of potential outcomes emerging from this analysis could be a starting point for developing AFCs for the Flint River. This scenario building and risk assessment process would provide an evaluation of whether costs (economic, social, and ecological) associated with departures from the SBA are acceptable, followed by the development of achievable strategies for addressing flow deficits. Sufficient technical information exists to guide management responses and a monitoring network is in place to provide feedback. The challenge lies with developing an institutional framework for engaging diverse social and economic interests in a process leading to AFCs defined by environmental stream flows that could address tradeoffs between ecological structure and function of the Flint River and the provision of various human

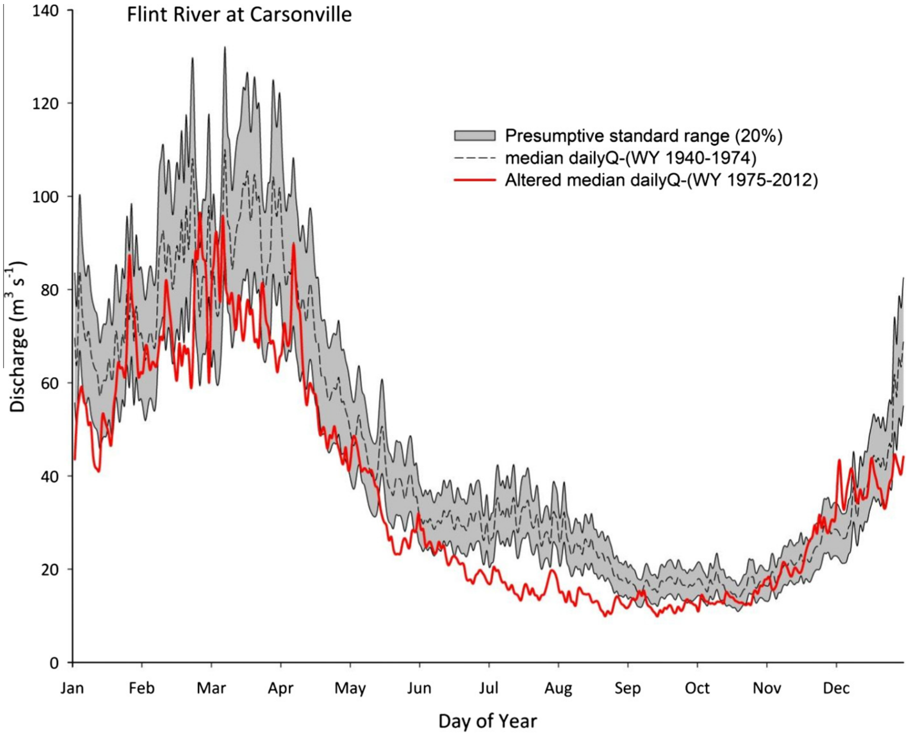

Fig. 8. Calculation of Presumptive Standard using the SBA from Richter et al. (2011). Data obtained from the Carsonville, GA gauge (USGS 02347500). Grey range represents median daily flow ±20%. Solid red line represents 'altered' flow conditions based on median daily flows calculated from WY 1975 to 2012.

water uses. Key constituents include water utilities, industrial users, recreational users, and the agricultural sector. The SBA approach is inherently adaptive, once goals for AFCs are set, data collection and assessment can proceed and management activities adjusted based on river- specific knowledge and economic/ecological interests.

6.3. Achievable future conditions provide the foundation for prioritizing conservation and management actions

Concerns over future water resources motivate immediate consideration of strategies to address vulnerabilities associated with extended periods of low flows in the Flint River. Increasing the availability of storage reservoirs is expensive and may be geologically challenging (Sun et al., 2013); therefore, efforts at reducing consumption might be emphasized over the short term. A number of approaches have been suggested for the Flint River (e.g., Emanuel and Rogers, 2012; Emanuel, 2014), such as better early recognition of drought conditions and faster responses in reducing *per capita* water use in response to anticipated shortages. The Flint River is already part of a National Oceanographic and Atmospheric Administration (NOAA) test program for regional drought early warning efforts (www.drought.gov/drought/content/regional-programs). Inclusion within this program indicates that monitoring capability is already in place, and water utilities could use NOAA seasonal outlooks to more aggressively impose water conservation measures before water storage reaches critical thresholds. Changing landscaping practices and improving the efficiency of lawn irrigation systems can also reduce water demand during seasonal dry periods. In municipal systems user demand approximately doubles during the growing season, largely due to landscape watering (Emanuel and Rogers, 2012). Another approach is improving water distribution and use efficiency through repair of leaks in distribution systems and incentives for improving end-user efficiencies. Several municipalities in the upper Flint have initiated programs to improve efficiency of distribution and household water use (e.g., Emanuel and Rogers, 2012). With the exception of infrastructure repair and improvement, many of the changes described above require water conservation encouraged either through public information campaigns or with progressive water pricing mechanisms.

Longer term responses to potential water shortage could involve systematic examination of water yield/balance at basin scales and adapting BMPs to enhance yields and reduce water loss. In urban areas, BMPs might include converting storm drain networks, which accelerate runoff, to 'green' infrastructure, which encourages water storage and infiltration (e.g. Jaffe, 2011). In rural areas of the lower Flint River basin, conversion of native forests to agriculture has accelerated water stress by replacing water conservative vegetation with water demanding crops (Ford et al., 2008; Brantley unpublished data). Intensive agriculture also requires irrigation during periods of low rainfall, putting additional seasonal stresses on water resources (Perry and Yager, 2011). In the lower Flint, improvements in agricultural irrigation efficiency are being adopted to reduce seasonal demand (Perry and Yager, 2011). However, there are limits to water savings that can be acquired through improved efficiency. Under some futures, retirement of some agricultural lands might provide the only feasible path to AFCs, suggesting some institutional structure to compensate landowners for foregone revenue (similar perhaps to the Conservation Reserve Program, but targeted to important components of this specific watershed).

At landscape scales, economically viable alternatives to water intensive irrigated agriculture need to be developed and evaluated. Adoption could be encouraged through conservation easements and incentives programs for reforestation. Programs have been initiated within the southeastern US and include USDA Regional Conservation Partnership Programs (RCPP, http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/farmbill/rcpp/) and the America's Longleaf Restoration Initiative (ALRI, http://www.

americaslongleaf.org/). While these programs promote land conversion, their potential to affect regional water yield/balance and contribute to restoration of river flows has not been assessed. This is a critical information need in developing achievable future conditions for water resources in the southeastern US.

7. Summary and conclusions

In the context of using AFCs to guide conservation and management strategies, establishing current conditions, developing scenarios for the future, and assessing risk is a largely *technical* process; while determining AFCs is a collaborative *social* process between stakeholders and technical experts. Technical information can provide insight into future biophysical envelopes; however, stakeholder involvement is essential for determining social and policy goals. This process emphasizes the need for strategies or forest management actions that are realistic given ecological and social-economic constraints, have specific timelines for implementation, and have measurable outcomes to evaluate success (e.g., Maxwell et al., 2015). Critical to this process is developing a new suite of mitigative and adaptive BMP's that are applied at a regional scale. Although uncertainty is inherent in projections of future climate and land use, there is abundant evidence that rapid changes are altering forest ecosystem function and species distributions, and some of these changes are irreversible, resulting in novel ecosystems. Management approaches based solely on historic or current conditions are limited in their ability to sustain ecosystem services critical to an expanding human population. Understanding of the ecological past and current dynamics is necessary to establish baseline conditions, but not sufficient to guide decision-making. Instead, these baselines must be applied in scenario-based forecasting to generate a range of possible futures that can then be analyzed in a risk-based approach. These futures should include a diversity of land uses. Strategies for management must be broadened, as public lands are not sufficient to sustain ecosystem services for society in regions dominated by private land, such as the southeastern U.S. The notion of public versus private management responsibility is particularly untenable for rivers, which cross large sections of landscape under a variety of uses. Scientists, managers, policymakers, and stakeholder are therefore challenged to collaborate across political boundaries and spatial and temporal scales. New approaches are needed that anticipate and guide ecosystems in directions that mitigate undesirable outcomes. This process will necessarily be adaptive as baseline conditions change, future scenario projections are updated, and societal needs shift with a growing and diversifying population. The scientific community is tasked with advancing understanding of ecological dynamics and their contribution to ecosystem services, improving simulation models, and communicating their findings with managers and stakeholders. Together with scientists, managers will have to design and implement monitoring programs that are crucial to appropriate management responses. The critical need to provide an early warning of unexpected changes suggests that it will be necessary to expand monitoring networks, including approaches such as citizen science initiatives (Conrad and Hilchey, 2011; Aceves-Bueno et al., 2015).

Our framework provides a starting point to move towards AFCs, illustrated with examples from forest wildfire and water management in the southeastern U.S. It builds on work including the forest management resistance- resilience- transition framework of Millar et al. (2007), which could be incorporated as part of the process to determine ACFs. It is also consistent with environmental flows methodology, often proposed as an approach for developing water allocation strategies (Poff and Zimmerman, 2010). We anticipate that points along the cycle will be updated, and our framework will be adapted as information becomes available and dynamics change. In an uncertain future of rapid change and abrupt, unforeseen transitions, adjustments in management approaches will be necessary and some actions will fail. However, it is increasingly evident that the greatest risk is posed by continuing to implement strategies inconsistent with and not informed by current understanding of our novel future.

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References

Aceves-Bueno, E., Adeleye, A.S., Bradley, D., Brandt, W.T., Callery, P., Feraud, M., Garner, K.L., Gentry, R., Huang, Y., McCullough, I., Pearlman, I., Sutherland, S.A., Wilkinson, W., Yang, Y., Zink, T., Anderson, S.E., Tague, C., 2015. Citizen science as an approach for overcoming insufficient monitoring and inadequate stakeholder buy-in in adaptive management: criteria and evidence. Ecosystems 18, 493–506.

Agee, J.L., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., Weatherspoon, C.P., 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecol. Manag. 127, 55–66.

Agrawal, A., Cashore, B., Hardin, R., Shepherd, G., Benson, C., Miller, D., 2013. Economic contributions of forests. In: Background Paper 1, United Nations Forum on Forests 10th Session. Instanbul.

Ardón, M., Morse, J., Colman, B., Bernhardt, E.S., 2013. Drought-induced saltwater incursion leads to increased wetland nitrogen export. Glob. Change Biol. 19, 2976–2985. http://dx.doi.org/10.1111/gcb.12287.

Arvor, D., Durieux, L., Andres, S., LaPorte, M.-A., 2013. Advances in geographic object-based image analysis with ontologies: a review of main contributions and limitations from a remote sensing perspective. ISPRS J. Photogramm. 82, 125–137.

Aust, W.M., Blinn, C.R., 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: and overview of water quality and productivity research during the past 20 years (1982–2002). Water Air Soil Poll.: Focus 4, 5–36.

Bagley, J.E., Desai, A.R., Harding, K.J., Snyder, P.K., Foley, J.A., 2014. Drought and deforestation: has land cover change influenced recent precipitation extremes in the Amazon? J. Climate 27. http://dx.doi.org/10.1175/JCLI-D-12-00369.1.

Bahro, B., Barber, K.H., Sherlock, J.W., Yasuda, D.A., 2007. Stewardship and fireshed assessment: a process for designing a landscape fuel treatment strategy. In: USDA Forest Service GTR PSW-203.

Benke, A.C., 1990. A perspective on America's vanishing streams. J. North Am. Benthol. Soc. 9, 77–88.

Bhoi, S., Qu, J.J., Dasgupta, S., 2009. Multi-sensor study of aerosols from 2007 Okefenokee forest fire. J. Appl. Remote Sens. 3 (031501). http://dx.doi.org/10.1117/1.3078070.

Bradley, B.A., Wilcove, D.S., Oppenheimer, M., 2010. Climate change increases risk of plant invasion in the Eastern United States. Biol. Invasions 12, 1855–1872.

Burr, B.M., Mayden, R.L., 1992. Phylogenetics and North American freshwater fishes. In: Mayden, R.W. (Ed.), Systematics, Historical Ecology, and North American Freshwater Fishes. Stanford University Press, Stanford, pp. 18–75.

Butler, B.J., Wear, D.N., 2013. Forest Ownership dynamics of Southern forests, in: Wear, D.N., Greis, J.G., (Eds.), The Southern Forest Futures Project, USDA Forest Service, GTR SRS-178. Ashville, pp. 103–122.

Caldwell, P., Muldoon, C., Ford-Miniat, C., Cohen, E., Krieger, S., Sun, G., McNulty, S., Bolstad, P.V., 2014. Quantifying the role of National Forest System lands in providing surface drinking water supply for the Southern United States. In: USDA Forest Service, GTR SRS-197. Asheville.

Carlisle, D.M., Wolock, D.M., Meador, M.R., 2011. Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Front. Ecol. Environ. 9, 264–270.

Carpenter, S.R., Folke, C., Scheffer, M., Westley, F., 2009. Resilience: accounting for the non-computable. Ecol. Soc. 14, 13, <http://www.ecologyandsociety.org/vol14/iss1/art13/>.

Chapin III, F.S., Folke, C., Kofinas, G.P., 2009. A framework for understanding change. In: Chapin, F.S. (Ed.), Principles of Ecosystem Stewardship. Springer-Verlag, Berlin, pp. 3–28. http://dx.doi.org/10.1007/978-0-387-73033-2.

Christensen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.F., Parsons, D.J., Peterson, C.H., Turner, M. G., Woodmansee, R.G., 1996. The report of the ecological society of America committee on the scientific basis for ecosystem management. Ecol. Appl. 6, 665–691. http://dx.doi.org/10.2307/2269460.

Conrad, C.C., Hilchey, K.G., 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. Environ. Monit. Assess. 176, 273–291.

Couch, C.A., Hopkins, E.H., Hardy, P.S., 1996. Influences of environmental settings on aquatic ecosystems in the Apalachicola–Chattahoochee–Flint River basin. In: USGS Water-Resources Investigations Report 95-4278. Reston.

Dale, V.H., Brown, S., Haeuber, R., Hobbs, N.T., Huntley, N., Naiman, R.J., Riebsame, W.E., Turner, M.G., Valone, T., 2000. Ecological principles and guidelines for managing the use of land. Ecol. Appl. 10, 639–670.

Dickinson, J.L., Shirk, J.L., Bonter, D.N., Bonney, R.E., Crain, R.L., Martin, J., Phillips, T., Purcell, K.A., 2012. The current state of citizen science as a tool for ecological research and public engagement. Front. Ecol. Environ. 10, 291–297.

Edwards, L., Ambrose, J., Kirkman, L.K., 2013. The Natural Communities of Georgia. University of Georgia Press, Athens.

Emanuel, B., 2014. Upper Flint River Resiliency Action Plan. American Rivers. Atlanta <http://www.AmericanRivers.org/flintworkinggroup>.

Emanuel, B., Rogers, G., 2012. Running Dry: Challenges and Opportunities in Restoring Healthy Flows in Georgia's Upper Flint River Basin. American Rivers. Atlanta <http://www.AmericanRivers.org/RunningDry>.

Famiglietti, J.S., Rodell, M., 2013. Water in the balance. Science 340, 1300–1301.

Famiglietti, J.S., Cazenave, A., Eiker, A., Reager, J.T., Rodell, M., Velicogna, I., 2015. Satellites provide the big picture. Science 349, 684–685.

FAO and JRC, 2012. Global forest land-use change 1990–2005. In: Lindquist, E.J., D'Annunzio, R., Gerrand, A., MacDicken, K., Achard, F., Beuchle, R., Brink, A., Eva, H.D., Mayaux, P., San-Miguel-Ayanz J., Stibig, H-J., (Eds.), FAO Forestry Paper No. 169. Food and Agriculture Organization of the United Nations and European Commission Joint Research Centre, Rome.

Fekete, B.M., Robarts, R.D., Kumagai, M., Nachtnebel, H.-P., Odada, E., Zhulidov, A.V., 2015. Time for in situ renaissance. Science 349, 685–686.

Ford, C.R., Mitchell, R.J., Teskey, R.O., 2008. Water table depth affects productivity, water use, and the response to nitrogen addition in a savanna system. Can. J. Forest Res. 38, 2127–2218.

Freeman, M.C., Buell, G.R., Hay, L.E., Hughes, W.B., Jacobson, R.B., Jones, J.W., Jones, S. A., LaFontaine, J.H., Odum, K.R., Peterson, J.T., Riley, J.W., Schlinder, J.S., Shea, C., Weaver, J.D., 2012. Linking river management to species conservation using dynamic landscape-scale models. River Res. Appl. http://dx.doi.org/10.1002/rra.2575.

Gaither, C.J., Poudyal, N.C., Goodrick, S., Bowker, J.M., Malone, S., Gan, J., 2011. Wildland fire risk and social vulnerability in the Southeastern United States: an exploratory spatial data analysis approach. Forest Policy Econ. 13, 24–36.

Golladay, S.W., Gagnon, P., Kearns, M., Battle, J.M., Hicks, D.W., 2004. Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. J. North Am. Benthol. Soc. 23, 494–506.

Gunderson, L.H., 2000. Ecological resilience – in theory and application. Ann. Rev. Ecol. Syst. 31, 425–439.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R. M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.-A., Townshend, J.R., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci. Adv. 2015 (1), e1500052.

Hargrove, W.H., Spruce, J.P., Gasser, G.E., Hoffman, F.M., 2009. Toward a national early warning system for forest disturbances using remotely sensed canopy phenology. Photogramm. Eng. Rem. Sens. 75, 1150–1156.

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., Norton, D., Ojima, D., Richardson, D.M., Sanderson, E.W., Valladares, F., Vila, M., Zamora, R., Zobel, M., 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. Global Ecol. Biogeogr. 15, 1–7.

Hobbs, R.J., Higgs, E., Harris, J.A., 2009. Novel ecosystems: implications for conservation and restoration. Trends Ecol. Evol. 24, 599–605.

Hobbs, R.J., Higgs, E.S., Hall, C.M., 2013. Novel Ecosystems: Intervening in the New Ecological World Order. John Wiley & Sons Ltd, Chichester.

Hobbs, R.J., Higgs, E., Hall, C.M., Bridgewater, P.M., Chapin III, F.S., Ellis, E.C., Ewel, J.J., Hallett, L.M., Harris, J., Hulvey, K.B., Jackson, S.T., Kennedy, P.L., Kueffer, C., Lach, L., Lantz, T.C., Lugo, A.E., Mascaro, J., Murphy, S.D., Nelson, C.R., Perring, M.P., Richardson, D.M., Seastedt, T.R., Standish, R.J., Starzomski, B.M., Suding, K.N., Tognetti, P.M., Yakob, L., Yung, L., 2014. Managing the whole landscape: historical, hybrid, and novel ecosystems. Front. Ecol. Environ. 12, 557–564.

IPCC, 2007. Climate change 2007: synthesis report. In: Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva.

IPCC, 2014. Climate change 2014: synthesis report. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva.

Iverson, L.R., Matthews, S.N., Prasad, A.M., Peters, M.P., Yohe, G., 2012. Development of risk matrices for evaluating climatic change responses of forested habitats. Climatic Change 114, 231–243.

Jaffe, M., 2011. Reflections on green infrastructure economics. Environ. Pract. 12, 357–365.

Kao, R.H., Gibson, C.M., Gallery, R.E., Meier, C.L., Barnett, D.T., Docherty, K.M., Blevins, K.K., Travers, P.D., Azuaje, E., Springer, Y.P., Thibault, K.M., McKenzie, V. J., Keller, M., Alves, L.F., Hinckley, E.S., Parnell, J., Schimel, D., 2012. NEON terrestrial field observations: designing continental-scale, standardized sampling. Ecosphere, 3. http://dx.doi.org/10.1890/ES12-00196.1.

Kerr, J.T., Ostrovsky, M., 2003. From space to species: ecological applications for remote sensing. Trends Ecol. Evol. 18, 299–305.

Kirkman, L.K., Mitchell, R.J., Helton, R.C., Drew, M.B., 2001. Productivity and species richness across an environmental gradient in a fire-dependent ecosystem. Am. J. Bot. 88, 2119–2128.

Klepzig, K., Shelfer R., Choice, Z., 2014. Outlook for coastal plain forests: a subregional report from the Southern Forest Futures Project. In: USDA Forest Service, GTR SRS-GTR-196. Ashville.

Likens, G., 2001. Biogeochemistry, the watershed approach: some uses and limitations. Mar. Freshwat. Res. 52, 5–12.

Lindenmayer, D., Likens, G., 2010. The science and application of ecological monitoring. Biol. Conserv. 143, 1317–1328.

Liu, Y.Q., Goodrick, S.L., Stanturf, J.A., 2013a. Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. Forest Ecol. Manag. 294, 120–135.

Liu, Y.Q., Prestemon, J., Goodrick, S.L., Holmes, T.P., Stanturf, J.A., Vose, J.M., Sun, G., 2013b. Future wildfire trends, impacts and mitigation options in the Southern United States. In: Vose, J.M., Klepzig, K. (Eds.), Climate Change Adaptation and Mitigation Management Options. CRC Press, Boca Raton, pp. 85–126.

Lockaby, G., Nagy, C., Vose, J. M., Ford, C. R., Sun, G., McNulty, S., Caldwell, P., Cohen, E., Moore Myers, J., 2013. Forests and water. In: Wear, D.N., Greis, J.G., (Eds.), The Southern Forest Futures Project: Technical Report. USDA Forest Service GTR SRS-178. Asheville, pp. 309–339.

Lower Flint-Ochlockonee Regional Water Plan, 2011. <http://www.flintochlockonee.org/documents/LFO_Adopted_RWP.pdf> (accessed September 2015).

Maes, J., Egoh, B., Willemen, L., Liquete, C., Vihervaara, P., Schager, J.P., Grizzetti, B., Drakou, E.V., La Notte, A., Zulian, G., Bouraoui, F., Paracchini, M.L., Bratt, L., Bidoglio, G., 2012. Mapping ecosystem services for policy support and decision making in the European Union. Ecosyst. Serv. 1, 31–39.

Maxwell, S.L., Milner-Gulland, E.J., Jones, J.P.G., Knight, A.T., Bunnefeld, N., Nuno, A., Bal, P., Earle, S., Waterson, J.E.M., Rhodes, J.R., 2015. Being smart about SMART environmental targets. Science 347, 1075–1076.

McDowell, W.H., 2015. NEON and STREON: opportunities and challenges for the aquatic sciences. Freshwat. Sci. 34, 386–391.

McNulty, S., Myers, J.M., Caldwell P., Sun, G., 2013. Climate change summary. In: Wear, D.N., Greis, J.G., (Eds.), The Southern Forest Futures Project. USDA Forest Service GTR SRS-178. Ashville, pp. 27–44.

Melillo, J.M., Richmond, T., Yohe, G.W., 2014. Climate change impacts in the United States: the third national climate assessment. Global Change Res. Prog. http://dx.doi.org/10.7930/J0Z31WJ2.

Melvin, M., 2012. National Prescribed Fire Use Survey Report. Coalition of Prescribed Fire Councils Technical Report 01-12. Newton.

Mercer, D.E., Cooley, D., Hamilton, K., 2011. Taking Stock: Payments for Forest Ecosystem Services in the United States. Forest Trends Association, Washington, DC.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17, 2145–2151.

Milly, P.C.D., Betancourt, J., Falkenmark, M., 2008. Climate change: stationarity is dead: whither water management? Science 319, 573–574.

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

Moyle, P.B., Mount, J.F., 2007. Homogenous rivers, homogenous faunas. Proc. Nat. Acad. Sci. USA 104, 5711–5712.

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

Neves, R.J., Bogan, A.E., Williams, J.D., Ahlstedt, S.A., Hartfield, P.W., 1997. Status of aquatic mollusks in the southeastern United States: a downward spiral of diversity. In: Benz, G.W., Collins, D.E., (Eds.), Aquatic Fauna in Peril: The Southeastern Perspective. Southeastern Aquatic Research Institute, Lenz Design and Communications, Decatur, pp. 43–85.

North, M., Collins, B.M., Stephens, S., 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. J. Forest. 110, 392–401.

Odman, T., Hu, Y., Russel, A., 2007. Forecasting the impacts of wildfires. In: 2007 CMAQ User Workshop, Chapel Hill <http://www.cmascenter.org>.

Ojima, D.S., Iverson, L.R., Sohngen, B.L., 2012. Appendix 2: risk-based framework and risk case studies: Risk-based framework for evaluating changes in response thresholds and vulnerabilities. In: Vose, J.M., Peterson, D.L., Patel-Weynand, T., (Eds.), Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector. USDA Forest Service, GTR PNW-GTR-870. Portland, pp. 243–245.

Ojima, D.S., Iverson, L.R., Sohngen, B.L., Vose, J.M., Woodall, C.W., Domke, G.M., Peterson, D.L., Littell, J.S., Matthews, S.N., Prasad, A.M., Peters, M.P., Yohe, G.W., Friggens, M.M., 2014. Risk assessment. In: Petersen, D.L., Vose, J.L., Patel-Weyland, T., (Eds.), Climate Change and United States Forests. Advances in Global Change Research 57, pp. 223–244, http://dx.doi.org/10.1007/978-94-007-7515-2_9.

Olden, J.D., Poff, N.L., 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. Riv. Res. Appl. 19, 101–121.

Perry, C., Yager, R., 2011. Irrigation water conservation efforts at the UGA C.M. Stripling Irrigation Research Park. In: Proceedings of the 2011 Georgia Water Resources Conference. Athens.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J-.M., Tucker, C.J., Stenseth, N.C., 2005. Using satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol. Evol. 20, 503–510.

Pickett, S.T.A., Parker, V.T., Fiedler, P.L., 1992. The new paradigm in ecology: implications for conservation biology above the species level. In: Fiedler, P.L., Jain, S.K. (Eds.), Conservation Biology: The Theory and Practice of Nature Conservation, Preservation, and Management. Chapman and Hall, New York, pp. 65–88.

Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwat. Biol. 55, 194–205.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keefe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwat. Biol. 55, 147–170.

Prato, T., 2008. Accounting for risk and uncertainty in determining preferred strategies for adapting to future climate change. Mitig. Adapt. Strateg. Glob. Change 13, 47–60.

Prud'homme, B.A., Greis, J.G., 2002. Best management practices in the south. In: Wear, D.N., Greis, J.G., (Eds.), The Southern Forest Resource Assessment: Technical Report. USDA Forest Service, GTR SRS-53. Ashville, pp. 519–535 (chapter 22).

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., McKeefry, J.F., 2005. The wildland–urban interface in the United States. Ecol. Appl. 15, 799–805.

Reager, J.T., Thomas, B.F., Famiglietti, J.S., 2014. River basin flooding potential inferred using GRACE gravity observations at several months lead time. Nat. Geosc. 7, 588–592.

Reed, M.S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C.H., Stringer, L.C., 2009. Who's in and why? A topology of stakeholder analysis methods for natural resource management. J. Environ. Manag. 90, 1933–1949.

Richter, B.D., 2009. Re-thinking environmental flows: from allocations and reserves to sustainability boundaries. Riv. Res. Appl. http://dx.doi.org/10.1002/rra.1320.

Richter, B.D., Davis, M.M., Apse, C., Konrad, C., 2011. A presumptive standard for environmental flow protection. Riv. Res. Appl. http://dx.doi.org/10.1002/rra.1511.

Rieman, B.E., Smith, C.L., Naiman, R.J., Ruggerone, G., Wood, C.C., Huntly, N., Merrill, E.N., Alldredge, J.R., Bisson, P.A., Congleton, J., Fausch, K., Levings, C., Pearcy, W., Scarnecchia, D., Smouse, P., 2015. A comprehensive approach for habitat restoration in the Columbia Basin. Fisheries 40, 124–135.

Rugel, K., Jackson, C.R., Romeis, J.J., Golladay, S.W., Hicks, D.W., Dowd, J.F., 2012. Effects of irrigation withdrawals on streamflows in a karst environment: lower Flint River Basin, Georgia, USA. Hydrol. Process. 26, 523–534.

Sargent, L.W., Golladay, S.W., Covich, A.P., Opsahl, S.P., 2011. Physicochemical habitat association of a native and non-native crayfish in the lower Flint river, Georgia: implications for invasion success. Biol. Invasions 13, 499–511.

Schimel, D., Keller, M., 2015. Big questions, big science: meeting the challenges of global ecology. Oecologia. http://dx.doi.org/10.1007/s00442-015-3236-3.

Seastedt, T.R., Hobbs, R.J., Suding, K.N., 2008. Management of novel ecosystems: are novel approaches required? Front. Ecol. Environ. 6, 547–553.

Sheppard, C.S., Burns, B., Stanley, M.C., 2014. Predicting plant invasions under climate change: are species distribution models validated by field trials? Glob. Change Biol. 20, 2800–2814.

Shortle, J.S., Horan, R.D., 2013. Policy instruments for water quality protection. Ann. Rev. Resour. Econ. 5, 111–138.

Stanturf, J.A., Goodrick, S.L., 2013. Fire. In: Wear D.N., Greis, J.G., (Eds.), The Southern Forest Futures Project. USDA Forest Service GTR SRS-178. Ashville, pp. 509–529.

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

Stephens, S.L., Agee, J.K., Fule, P.Z., North, M.P., Romme, W.H., Swetnam, T.W., Turner, M.G., 2013. Managing forests and fire in changing climates. Science 342, 41–42.

Sun, G., McNulty, S.G., Moore, J.A., Cohen, E.C., 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. J. Am. Water Resour. Assoc. 44, 1441–1457.

Sun, G., Caldwell, P.V., McNulty, S.G., Georgakakos, A.P., Arumugam, S., Cruise, J., McNider, R.T., Terando, A., Conrads, P.A., Feldt, J., Misra, V., Romolo, L., Rasmussen, T.C., Marion, D.A., 2013. Impacts of Climate Change and Variability on Water Resources in the Southeast USA. USDA Forest Service, NCA Southeast Technical Report 204-234. Ashville.

Terando, A.J., Costanza, J., Belyea, C., Dunn, R.R., McKerrow, A., Collazo, J.A., 2014. The southern megalopolis: using the past to predict the future of urban sprawl in the southeast U.S. PLOSone 9, e102261, http://dx.doi.org/10.1371/journal.pone.0102261.

Thomas, A.C., Reager, J.T., Famiglietti, J.S., Rodell, M., 2014. A grace-based water storage deficit approach for hydrological drought characterization. Geophys. Res. Lett. 41, 1537–1545.

Upper Flint Regional Water Plan, 2011. <http://www.upperflint.org/documents/UFL_Adopted_RWP.pdf> (accessed September 2015).

van den Avyle, M.J., Evans, J.W., 1990. Temperature selection by Striped Bass in a Gulf of Mexico coastal river system. N. Am. J. Fish. Manag. 10, 58–66.

Wear, D.N., 2013. Forecasts of land uses. In: Wear, D.N., Greis, J.G., (Eds.), The Southern Forest Futures Project. USDA Forest Service, GTR SRS-178. Ashville, pp. 45–72.

Wear, D.N., Greis, J.G., 2013. The Southern Forest Futures Project: Technical Report, USDA Forest Service, GTR SRS-178. Ashville.

Westgate, M.J., Likens, G.E., Lindenmayer, D.B., 2013. Adaptive management of biological systems: a review. Biol. Conserv. 158, 128–139.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S., 2011. Status and future of the forest health indicators program of the USA. Environ. Monit. Assess. 177, 419–436.

Yin, Z., 1993. Fire regime of the Okefenokee Swamp and its relation to hydrological and climatic conditions. Int. J. Wildland Fire 3, 229–240.

Yohe, G., Leichenko, R., 2010. Adopting a risk-based approach. Ann. NY. Acad. Sci., Spec. Iss. New York City Panel Clim. Change 196, 29–40.

Zhang, Y., He, H.S., Yang, J., 2008. The wildland–urban interface dynamics in the southeast U.S. from 1990 to 2000. Landsc. Urban Plan. 85, 155–162.

Zhang, R., Delworth, T.L., Sutton, R., Hodson, D.L.R., Dixon, K.W., Held, I.M., Kushnir, Y., Marshall, J., Ming, Y., Msadek, R., Robson, J., Rosati, A.J., Ting, M.-F., Vecchi, G. A., 2013. Have aerosols caused the observed Atlantic multidecadal variability? J. Atmos. Sci. 70, 1135–1144.