15 Planning for an Uncertain Future

Restoration to Mitigate Water Scarcity and Sustain Carbon Sequestration

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INTRODUCTION

The desired future conditions of longleaf pine (*Pinus palustris*) can be described by ecosystem structural characteristics as well as by the provision of ecosystem services. Although the desired structural characteristics of restored longleaf pine ecosystems have been described at length, these characteristics deserve a brief review here because ecosystem structure directly contributes to the provision of key ecosystem services and helps differentiate these forests from other land uses in the southeastern United States. Briefly, upland longleaf pine stands managed with frequent fire are characterized by low basal area, an open canopy, a sparse midstory, and a diverse uninterrupted herbaceous layer (Walker and Peet 1983; Platt 1999; Kirkman et al. 2001; McIntyre 2012). Over the long term, emphasizing the single-tree selection method of canopy harvesting will produce an uneven-aged stand structure that adds to complexity and maintains both ecosystem services and long-term economic value (Mitchell et al. 2006). Achieving this characteristic stand structure often serves as a first indicator that restoration goals are being met (Rasser 2003; McIntyre 2012).

Many of the known longleaf pine ecosystem services—such as biodiversity, wildlife habitat, and occupancy by endangered species—depend on the characteristic ecosystem structure. Although the achievement of desired conditions can often be assessed based on only stand structure or species composition (or both), the full value of longleaf pine restoration for the restoration of other ecosystem services is largely unknown.

In this chapter, we review characteristics of longleaf pine forests in the context of protecting and enhancing water resources in the Southeast and sequestering carbon (C) for climate change mitigation. Although our primary focus is on protecting water resources, we also review C sequestration issues and describe the trade-offs between managing lands to mitigate water scarcity while simultaneously promoting long-term C sequestration. We suggest that the societal benefits of protecting water and C resources by restoring longleaf pine are often unrecognized and undervalued, but have the potential to complement goals already established for current restoration programs. Thus, a more complete understanding of how longleaf pine restoration affects fluxes and pools of both water and C could lead to increased incentives for longleaf pine restoration projects and enhanced opportunities for larger-scale restoration efforts.

CONTEXT FOR FOREST RESTORATION: CONTEMPORARY ISSUES OF WATER AND CARBON BUDGETS

Forests and Water

Forest Effects on Water Yield

Because forests are a critical source of clean and abundant water, forest management is an essential tool for management of water resources in the Southeast (Jackson et al. 2004; Lockaby et al. 2013; Caldwell et al. 2014; Marion et al. 2014). Although water quality is also a major concern in the Southeast, the primary focus of this chapter will be on managing quantity, specifically water yield. Here, we define water yield as the difference between incoming precipitation and water exiting the system as evapotranspiration (ET). Water yield is most often quantified at the watershed level, but the water budget concept can also be applied to the forest stand. Water yield contributes to multiple pools of water including streamflow, groundwater recharge, and replenishment of soil water storage.

Water Scarcity in the Southeast

In recent decades, a combination of population growth, expanding water use for agriculture, and increasing climate variability have stressed water supplies in the Southeast (Lockaby et al. 2013; Sun et al. 2013; Caldwell et al. 2016). Although inputs from precipitation are relatively high (> 1000 mm/year) in the Southeast compared to many arid regions, increasing demand has challenged long-standing policies and existing political structures in a region not historically accustomed to water scarcity (Ruhl 2005). Increasing water demands by the municipal and agricultural sectors have had a particularly large impact on streamflow and aquatic ecosystem services (Sun et al. 2008).

Much of the current focus on water management in the Southeast is on municipal water use. However, a relatively large percentage of these withdrawals are returned into surface waters, resulting in lower consumptive use compared to agricultural withdrawals (Richter 2014). Because agricultural water use is highly consumptive, it is more likely to have direct effects on stream and river discharge. This issue has been particularly apparent in the Coastal Plain (Figure 15.1), where many watersheds once dominated by longleaf pine have experienced exponential growth of center-pivot irrigation since the late 1960s (Pierce et al. 1984; Couch et al. 1996; Golladay et al. 2007). As demonstrated in Figure 15.2, row crop cultivation in the Southeast relies heavily on irrigation, and the proliferation of center-pivot irrigation systems has had a demonstrable effect on flow regimes (Couch et al. 1996; Golladay et al. 2007; Rugel et al. 2012; Golladay and Hicks 2013). The effect of agricultural water use in the Flint River and adjacent Chattahoochee River watersheds on downstream flow has been a major controversy for water managers and policy makers in Alabama, Florida, and Georgia since the early 1990s (Ruhl 2005), including a recent U.S. Supreme Court case (*Florida v. Georgia*) filed in 2013 that examined water apportionment in the region.

Ecological Consequences of Declining Streamflow

Changes in flow regimes of streams and rivers not only have social and economic impacts on human population centers and agriculture, but also impact aquatic ecosystems. In the Coastal Plain, Golladay and Hicks (2015) and McCormick and Baron (2015) demonstrated that aquatic ecosystems were at greatest risk from the historic low summer flows that dewatered critical habitat during droughts and reduced habitat quality in the pockets of water that remained. Such departures from

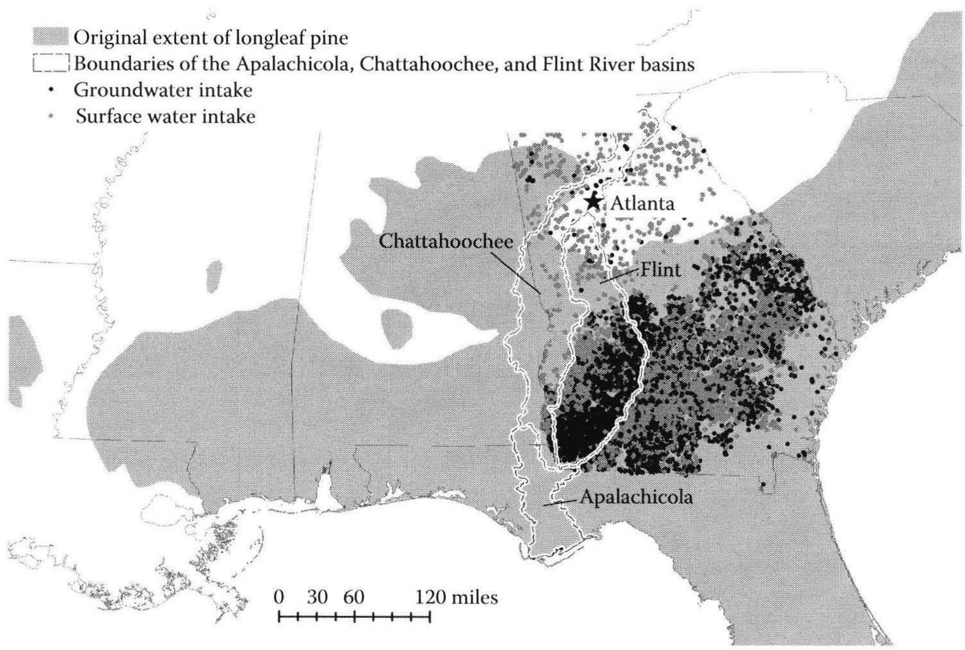

FIGURE 15.1 The overlap of the Apalachicola-Chattahoochee-Flint River basin with the historical range of longleaf pine in Georgia showing permitted groundwater and surface water intakes. (Map modified from Ware, S. et al., *Biodiveristy of the Southeastern United States: Lowland Terrestrial Communities*, John Wiley & Sons, New York, 1993. Source of data: Georgia Department of Natural Resources, Environmental Protection Division.)

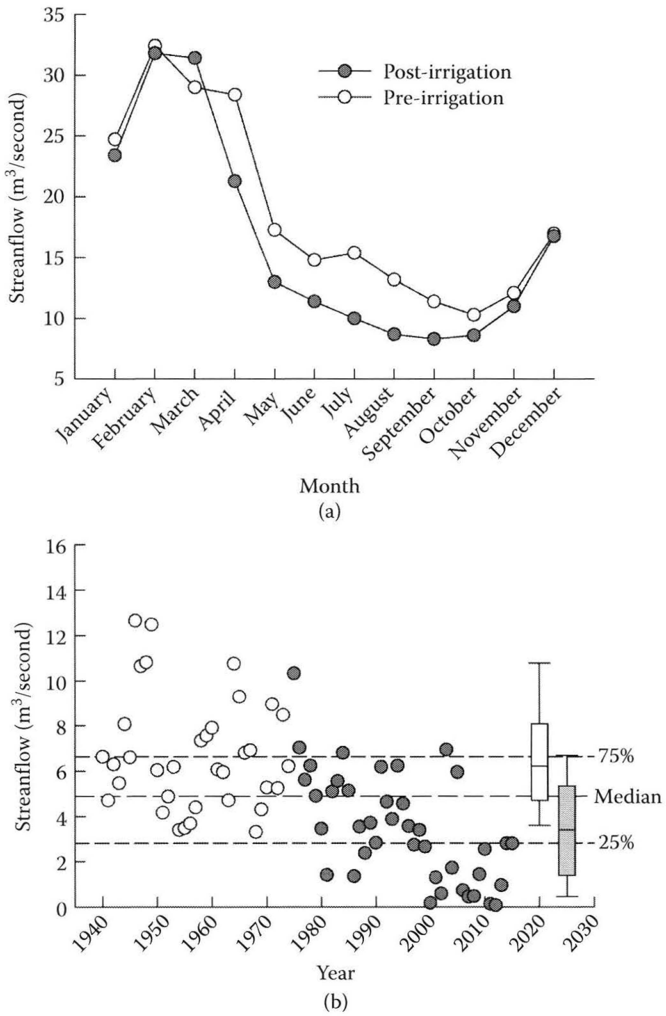

FIGURE 15.2 Observed changes in streamflow in the Ichawaynochaway Creek at Milford, GA (USGS 02353500) after the proliferation of center-pivot irrigation in the Southeast during the 1970s: (a) Differences in monthly median flow between pre-irrigation (1940–1974) and post-irrigation records (1975–2004), and (b) changes in 1-day minimum flows compared to long-term median. (Modified and updated from Golladay, S. W. et al., *Proceedings of the 2007 Georgia Water Conference*, University of Georgia, Athens, Georgia, 2007.)

historical minimums can harm fish, mussels, crustaceans, macroinvertebrates, and other aquatic life (van den Avyle and Evans 1990; Smith et al. 2015).

Altered flow regimes in major rivers also have negative consequences for estuaries and other downstream ecosystems (Fitzhugh and Richter 2004). Much of the current controversy surrounding flows in the Apalachicola-Chattahoochee-Flint River basin centers on damage to the health of Apalachicola Bay, a diverse and productive downstream ecosystem that supports an important oyster industry (Livingston 1991). Reduced freshwater input during the 2007–2008 drought resulted in significant increases in salinity followed by increases in oyster mortality (Petes et al. 2012). If issues of water scarcity in such systems are not substantively addressed in the near future, continued decreases in freshwater inputs—combined with sea level rise and increasingly frequent and severe droughts predicted under climate change—would have substantial deleterious effects on stream, river, and estuarine habitat and water quality—impacting both ecological and social systems (Sun et al. 2013).

Link between Water Scarcity and Land Management

Agricultural withdrawals have been the primary cause of water scarcity in recent decades, but some evidence suggests that the water balance in southern Georgia was changing even before the rapid expansion of center-pivot irrigation. Harper (1956) reported a lowering of the groundwater table in southern Georgia and cited similar earlier reports in many other parts of the United States following European settlement. Harper (1956) attributed the change in the water table, the reduction in cover of swamps, and the resultant loss of biodiversity to increasing water withdrawals for growing towns and cities. However, he also hypothesized that increases in ET, which resulted when natural vegetation such as longleaf pine and wiregrass was replaced by row crops, also had a role.

Globally, ET represents the second largest flux of water in terrestrial systems (after precipitation), with plant transpiration accounting for the majority of this flux (Jasechko et al. 2013; Good et al. 2015). By its very nature, ET represents consumptive use. Consequently, changes in land cover that affect ET at the watershed scale have direct effects on water yield. ET is also generally considered a conservative process in that it shows little variation from 1 year to the next; thus, natural interannual variations in rainfall tend to be reflected in water yield (Oishi et al. 2010). The earlier observations by Harper (1956) suggest that increases in ET from changes in land use since the beginning of European settlement have had a major impact on regional water balance. More importantly in the context of current regional water scarcity issues, this close coupling between land cover and water yield also suggests a potential path for mitigating water scarcity by emphasizing restoration projects that focus on reducing ET.

Carbon Sequestration

Forests and Carbon

Forests also play a critical role in the global C cycle (Jackson et al. 2005; Bonan 2008; Canadell and Raupach 2008; Lockaby et al. 2013; Caldwell et al. 2014). The potential of forests to sequester C has been the subject of considerable attention, both from scientists and from policy makers, as a tool to mitigate climate change by reducing net emissions of carbon dioxide—by far the most common greenhouse gas. U.S. forests currently sequester 173 Tg C/year, which is about 10% of C emissions from the U.S. energy and transportation sectors (Wear and Coulston 2015). Land use changes resulting from reforestation and afforestation shifted about 44 Tg C/year into the forest sector from 2010 to 2014 (Wear and Coulston 2015). Eastern forests, which provide nearly 80% of the C sink, are projected to provide nearly 90% by 2030 (Wear and Coulston 2015). Forest C accumulation is largely a function of forest type and age distribution, with the condition of eastern forests reflecting an ongoing recovery of a landscape that was largely cut over in the early 20th century.

Because of the critical role that forests play in C sequestration nationally, climate change mitigation policy logically focuses on protecting the vast C stores in forests and expanding their potential role as a C sink. Current U.S. projections show a gradual slowing of C accumulation overall (Wear and Coulston 2015) and the possibility that C transfers into forest ecosystems could slow and then reverse, thereby defining some serious challenges to the current policy goal. Policy initiatives focused on retaining forest uses will require incentives that overcome market-driven shifts in rural land uses and practices that increase the average annual C storage over the course of the management regime. C taxes would likely affect these outcomes, but other forms of inducement can influence landowner behaviors (van Kooten et al. 1995; Lubowski et al. 2006).

Carbon Sequestration in the Southeast

The Southeast has been identified as a particularly strong C sink based on high rates of net ecosystem exchange (NEE), where NEE represents the net balance between C gained from photosynthesis and C lost from respiration (Ingram et al. 2013; Novick et al. 2015). A detailed analysis of recent C dynamics (Coulston et al. 2015) confirmed the influence of management and regrowth in southeastern forests, where C sequestration in unharvested and undisturbed stands (144 Tg C/year) was nearly 100% higher than in harvested stands (77 Tg C/year). They also found that natural disturbances dampen the rates of C accumulation but do not lead to net emissions of C and that southeastern forests in particular have "room to grow," although at decreasing rates of accumulation than the rates observed in recent decades.

Land use change continues to reshape forests and their C pools. While forest area has increased slightly over the last 20 years, the flows into and out of forest use have been much larger (Coulston et al. 2015). Land use changes, especially exchanges between agriculture and forests, occur in response to changes in the relative economic returns from these uses in specific places. Overall, the steady transfer of forests to urban use has been offset by net flows of agricultural land into forests.

Environmental Trade-Offs of Carbon Sequestration

Much of the current management focus in the Southeast emphasizes intensive management for maximal biomass production. This type of management has both economic benefits for landowners and environmental benefits for climate change mitigation through C sequestration. However, it does little to address regional water scarcity issues, and it may exacerbate regional water stress under some circumstances based on the linkages among NEE, ET, and water yield (Jackson et al. 2005). In the following sections, we summarize the current state of knowledge about water and C cycling in longleaf pine, and we suggest future directions for studying the potential role of longleaf pine ecosystems in combining water scarcity mitigation with C sequestration.

CAN LONGLEAF PINE RESTORATION HELP REDUCE WATER SCARCITY?

Managing Forests for Water Yield

The concept of managing forests to augment water supplies is not new (Douglass 1983); however, several recent severe droughts and growing populations in the Southeast have revived awareness of these related issues and opportunities (Ford et al. 2011; J. Jones et al. 2012; Sun et al. 2015; Vose et al. 2016). Because forest thinning and harvesting often lead to increased annual water yield (Bosch and Hewlett 1983; Brown et al. 2005; Sun et al. 2015), the effects of droughts in the Southeast could potentially be mitigated by maintaining lower density forests with inherently lower ET (McLaughlin et al. 2013). Thus, large-scale restoration of the drought tolerant, low basal area, frequently burned longleaf pine forest could benefit water resources by reducing ET, translating to increased stream runoff or groundwater recharge (or both). Furthermore, lower densities would also increase resilience to drought by reducing water stress on the trees that remain after stand reductions (Kush et al. 2004; McDowell and Allen 2015).

Increasing forest cover reduces annual water yield under some circumstances. However, compared to alternative land cover types such as row crop agriculture and urban development, forest cover is better able to maintain water quality, reduce runoff pollution, stabilize baseflow, and mitigate stormflow (Anderson et al. 1976; Jackson et al. 2004; Sun et al. 2005; Lockaby et al. 2013; Ford et al. 2011). Although these benefits are realized with most types of forest cover, a possible unique benefit of restoring longleaf pine may lie in the potential of this forest type to serve as a source of relatively high water yield. Compared to other forests in the Southeast, restored longleaf pine has low annual ET rates (Figure 15.3), particularly when stands are maintained at low densities similar to those found in natural, frequently burned stands (Ford et al. 2008; McLaughlin et al. 2013; Novick et al. 2015; Whelan et al. 2015). This characteristically low ET, when coupled with a historical range that largely overlaps areas facing the most immediate threats from water scarcity (Figures 15.1 and 15.2), suggests that large-scale restoration of the longleaf pine ecosystem could represent a promising strategy to mitigate water stress in some southeastern watersheds.

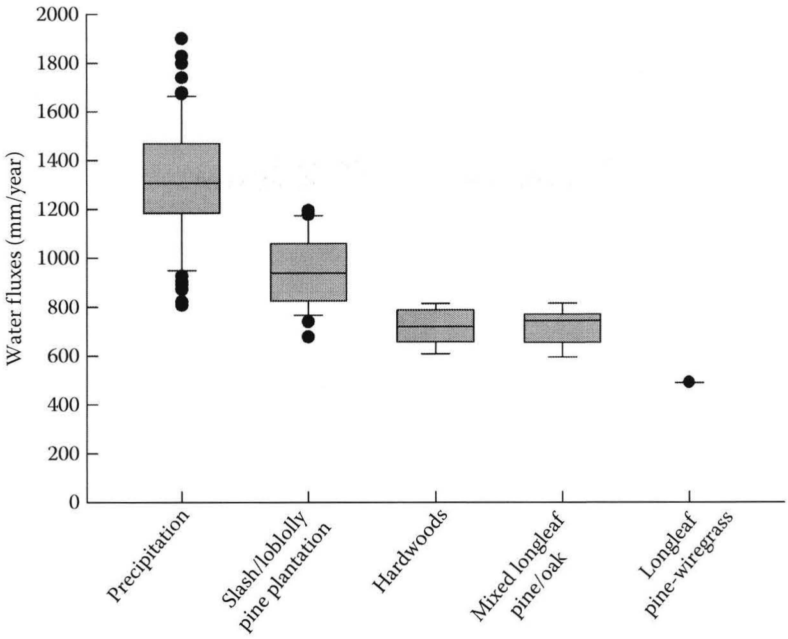

FIGURE 15.3 Annual precipitation distribution (1941–2010) at Dawson, GA (NOAA Station ID 092570) compared with annual evapotranspiration (ET) rates of dominant forest types in the Ichawaynochaway Creek watershed. (From S. Brantley, unpublished data. Precipitation data source: https://www.ncdc.noaa.gov/cdo-web/datatools/findstation. Evapotranspiration values are from a literature review of published ET values from the southeastern United States.)

Water Saving Characteristics of Longleaf Pine Ecosystems

Although specific data on ET partitioning in longleaf pine ecosystems have not been published, much of what we currently know about the structure and function of these ecosystems suggests several ways in which restoration and management with frequent fire would reduce ET. First, ET is likely to be lower in longleaf pine simply because its stand density is much lower than other southeastern forest types. Lower basal area translates into lower sapwood area and lower leaf area index values; these important structural characteristics interact to limit stand transpiration. Second, interception losses (the loss of incoming precipitation through direct evaporation during and after rainfall) are lower in the typically open-canopy longleaf pine with a midstory cover that is kept relatively sparse by frequent burning (McIntyre 2012); this results in further reductions in overall stand leaf area (Figure 15.4). This is a particularly important advantage for a fire-maintained longleaf pine forest, because midstory ET can be an important component of overall water use for other forest types (Johnson and Kovner 1956; Hamada et al. 2004; Powell et al. 2005; Brantley et al. 2013, 2015). Last, the reduced litter production of an open canopy and sparse midstory and the periodic consumption of forest floor biomass by frequent fires (Figure 15.5) may combine to reduce interception losses from the litter layer.

The effects of frequent prescribed fire on community composition also tend to favor lower ecosystem ET. Fire tends to select against aggressive, fast growing hardwood species such as water oak (*Quercus nigra*), laurel oak (*Q. laurifolia*), and black cherry (*Prunus serotina*). These species occur more typically in mesic or wet-mesic sites with richer soils, but they often encroach on upland longleaf pine stands when fire is absent or when cool weather or poor fuel conditions prevent fire from reaching adequate intensity (Jacqmain et al. 1999; McCay 2000; Varner and Kush 2004). These species are characterized by higher sapwood area (Figure 15.6) than southern red oak (*Q. falcata*), turkey oak (*Q. laevis*), and other typical ring-porous pyrophytic oak species that can only

(a)

(b)

FIGURE 15.4 Comparison between (a) a typical longleaf pine stand managed with a 2-year fire-return interval, and (b) a nearby site after 14 years of fire suppression. Note that fire suppression resulted in a rapid increase in mid-canopy leaf area, a shift in ground cover species composition, and an increase in forest floor biomass—all of which can contribute to higher rates of short-term carbon storage and stand evapotranspiration. (Photographs courtesy of Steven Brantley.)

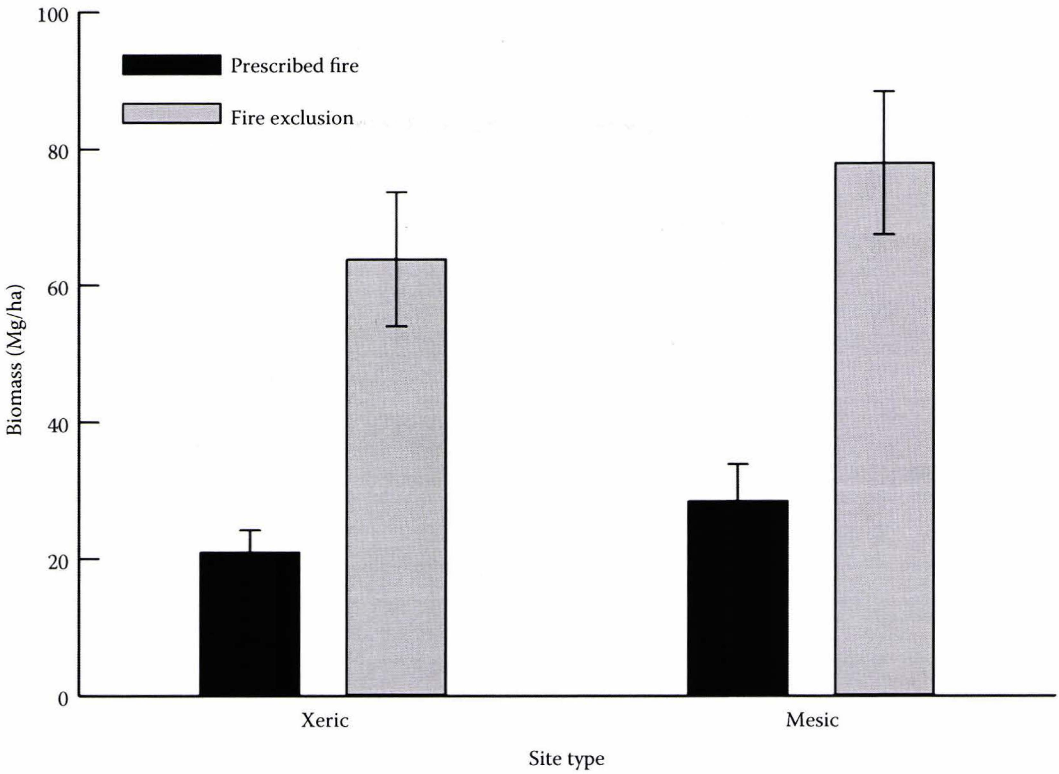

FIGURE 15.5 Forest floor biomass (litter) in regularly burned longleaf pine (2-year fire-return interval) and in stands subjected to 14 years of fire exclusion (From L. Boring, unpublished data.)

FIGURE 15.6 Differences in sapwood area, shown by red dye, between ring porous species (a), which tend to use relatively little water per unit of basal area and tend to be favored with frequent prescribed fire; and diffuse porous species (b), which tend to use substantially more water per unit of basal area. (Photographs courtesy of Ava Hoffman.)

transport water in their outer growth rings (Wullschleger et al. 1998). Shifts in species composition to more mesophytic species have been shown to result in relatively higher stand ET and concurrent decreases in water yield (Caldwell et al. 2016).

Finally, both longleaf pine and its frequent herbaceous codominant wiregrass (*Aristida stricta*) are conservative with respect to plant-level water use, although in different ways. Longleaf pine often demonstrates lower per-tree water use than other dominant, faster growing southeastern pine species under similar soil and climatic conditions (Martin 2000; Ford et al. 2008; Gonzalez-Benecke et al. 2011). In a comparison of longleaf pine and slash pine (*P. elliottii*), average daily transpiration for longleaf pine was 33% lower, mostly because of its relatively lower leaf area but also because of its higher stomatal sensitivity to soil moisture (Gonzalez-Benecke et al. 2011).

Water savings in longleaf pine ground cover are realized through higher water-use efficiency (the quantity of C fixed per unit of water consumed) and the relatively low leaf area of grasses and herbs. Many codominant herbaceous species in the longleaf pine ecosystem (Figure 15.7) tend to demonstrate higher water-use efficiency than the woody species that replace the herbaceous layer in the absence of fire (Ford et al. 2008; King et al. 2013; S. Brantley unpublished data). This is especially true of wiregrass and other warm season grasses (those with a C4 metabolism), which have photosynthesis pathways adapted to maximizing C fixation and minimizing water loss. Concurrently, when the herbaceous layer is grass-dominated, leaf area and productivity of the grasses are likely limited by their basal meristem anatomy, which severely limits exposure to sunlight (Knapp and Smith 2001; Knapp et al. 2008). These characteristics combine to reduce overall water use on the forest floor compared to sites dominated by the woody species that tend to encroach during prolonged fire intervals.

Stand Level Water Budgets in Longleaf Pine

All of the characteristics described above suggest that ET is lower in fire-maintained longleaf pine, but relatively few direct measurements of ET have been collected to test this hypothesis. To our knowledge, only three studies have reported annual ET in stands where longleaf pine was either a dominant or codominant canopy species. Using sap-flux measurements and scaled physiology data,

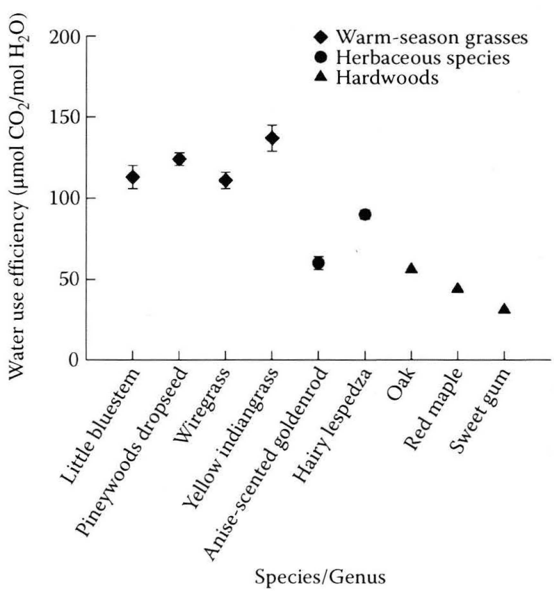

FIGURE 15.7 Water-use efficiency, defined as the number of carbon atoms fixed per unit of water used, for six herbaceous species that are commonly used in longleaf pine restoration programs (from S. Brantley, unpublished data) and three woody plants that are commonly recruited into the longleaf pine ecosystem under a regime of fire suppression. (From King, J. S. et al.,. *Bioscience,* 63, 102–117, 2013.)

Ford et al. (2008) reported that pure stands of longleaf pine and wiregrass use only 489 mm/year in mesic soils and even less in drier, sandhills soils. Powell et al. (2005) reported ET of 754 mm/year in a mature, low-density stand of mixed slash pine and longleaf pine in Florida. Whelan et al. (2015) reported a range of similar values (594–816 mm/year) for three southwestern Georgia sites in which longleaf pine was either dominant or codominant; this study provides the best range of potential spatial and temporal variation in ET for longleaf pine because multiple years of data were collected and the sites were located across a soil moisture gradient that is representative of longleaf pine habitat.

The forest ET values reported above and in Figure 15.3 were generally lower than most other land cover categories in the Southeast. However, the range of annual ET values reported was quite large, even among nearby sites (Powell et al. 2005; Ford et al. 2008; Whelan et al. 2015). Some of these inconsistencies can be attributed to methodological differences. For example, the studies that used stand-level energy balance methods reported higher ET than the estimates reported by Ford et al. (2008) for similar, nearby sites. Errors in scaling from tree and leaf-level measurements to the stand (Ford et al. 2008) could explain some of the inconsistencies between these results and the more integrated methods of Powell et al. (2005) and Whelan et al. (2015).

The three studies were different in several other important aspects. The longleaf pine stands studied by Powell et al. (2005) were also dominated by slash pine, which is known for higher per tree ET than longleaf (Gonzalez-Benecke et al. 2011). Additionally, ET values reported in Whelan et al. (2015) may not accurately represent ET for restored longleaf pine-wiregrass stands because the footprint (the area of forest sampled for ET) measured by the eddy covariance towers also contained patches of hardwood forest, forested wetlands, and agriculture.

Such inconsistencies indicate that analyses of ET data derived from eddy covariance need to be more spatially explicit for restored longleaf pine ecosystems. Eddy covariance and energy balance techniques collect large, nearly continuous data sets, which could be partitioned into discreet periods when ecosystem exchanges of water (and C) are primarily originating from segments of the footprint more strongly dominated by longleaf pine. Such an analysis would be supported by additional, semi-integrated measurements of the various ET components—such as sap flux, interception, and ground cover—in codominant species. These types of measurements would help account for transpiration by different species and provide estimates of soil evaporation, litter evaporation, and herbaceous transpiration as they relate to stand structure. The semi-integrated measurements of ET that partition water use among various components at the stand level could prove particularly valuable in helping watershed managers better understand the influence of fire (and thus fire suppression) on specific hydrologic fluxes and overall ET.

Despite their methodological differences, all of the studies described above agreed that longleaf pine has one of the lowest ET rates among various southeastern land cover types and that restored longleaf pine could be an ideal land cover for increasing water yield while maintaining the ability of forests to protect water quality.

LONGLEAF PINE POTENTIAL FOR CARBON SEQUESTRATION: BENEFITS, LIMITATIONS, AND UNKNOWNS

Current State of Knowledge

C sequestration by forests is generally expressed as net ecosystem productivity (NEP), the net accumulation of C in an ecosystem, and is often approximated using atmospheric measurements of NEE of CO_2 using eddy covariance. Assessments of C budgets in longleaf pine must also incorporate the effects of fire-induced C loss with NEE to quantify net ecosystem carbon balance (NECB). The relatively few studies that have quantified NECB in longleaf pine indicate that stands managed with frequent prescribed fire tend to be relatively small C sinks and can become short-term C sources under certain conditions (Whelan et al. 2013; Starr et al. 2014, 2016; Martin et al. 2015). For example, longleaf pine stands located in mesic soils in southwestern Georgia were small C sinks, whereas stands on drier (sandhills) soils were C neutral in the absence of fire (Whelan et al. 2013; Starr et al. 2015). However, the C neutral stands became small C sources when C losses from prescribed fire were factored into C budgets (Whelan et al. 2013).

Other forest types common in the Southeast—such as short-rotation pulpwood plantations and young (<100 years) fire-suppressed hardwoods—sequester substantially more C over the short term than longleaf pine (Clark et al. 2004; Bracho et al. 2013; Novick et al. 2015). Although short-term studies of NEE are useful for demonstrating the potential of ecosystems to sequester C, calculating annual NEE and NECB does not fully represent the long-term benefits of longleaf pine as a C sink. Studies of NEP and C accumulation in longleaf pine using forest survey methods have demonstrated substantial C gains in longleaf pine forests over time (Mitchell et al. 1999; Samuelson et al. 2014, 2017); and simulation modeling has shown long-term positive C accumulation in fire-maintained longleaf pine systems, although at a slower rate than other forest management strategies (Martin et al. 2015). Still, many questions remain regarding the value of longleaf pine restoration for sustainable C sequestration.

Uncertainties in Longleaf Pine Carbon Budgets

Climate Change, Ecosystem Resilience, and Reduction of Catastrophic Fire Risk

One of the greatest uncertainties in C science is how ecosystems will respond to changing climate conditions and how these changes will feedback to C sequestration. Although using frequent prescribed fire in longleaf pine can result in lower annual C accumulation in this forest type compared to others, prescribed fire may improve ecosystem resilience to changing climate and buffer against catastrophic events that would have large and long lasting effects on C budgets (Wiedinmyer and Hurteau 2010). Climate projections for the Southeast suggest that mean annual temperature will increase 4°C–8°C by 2100 (Carter et al. 2014). Projected precipitation changes are less certain. However, longer, more frequent, and more intense droughts are expected, and hotter and drier weather increases the likelihood of catastrophic wildfires (Carter et al. 2014). Frequent prescribed fire reduces fuel loading, thereby greatly reducing the risk of catastrophic, stand-replacing fires that would accompany hotter and drier future conditions. Preempting such wildfires through sustained fuel reduction would allow the resources normally directed toward fire suppression or postfire restoration to be directed toward proactive management programs with possible long-term cost savings, reduced risk to human life and property, reduced risks to human health from smoke emissions, protection of water quality, and long-term reduction in fire-related CO_2 emissions (Kush et al. 2004; Wiedinmyer and Hurteau 2010; Mitchell et al. 2014).

Knowing the balance between frequent (but small) C losses from prescribed fire and the potential large C losses from wildfire is paramount to future policy decisions. Although prescribed fire results in an immediate loss of biomass C as CO_2 through combustion, the risk of massive and long-term C loss from catastrophic stand-replacing fires is greatly reduced when longleaf pine stands are actively managed with prescribed fire. In fire-prone forest stands of western states, Wiedinmyer and Hurteau (2010) estimated that the targeted application of prescribed fire in dry forests reduced fire-related CO_2 emissions ≥ 18%–25% over the long term by mitigating the risks of catastrophic wildfires, suggesting that C releases during wildfires can more than offset the C sequestration benefits of fire suppression.

Black Carbon in Longleaf Pine

A second uncertainty surrounding the use of frequent fire in longleaf pine C budgets is the role of black C. Although a large proportion of fuel is converted to CO_2 through combustion, a substantial proportion of biomass C is transformed by incomplete combustion into a large and diverse set of molecules often collectively labeled black C (Goldberg 1985; Forbes et al. 2006; Czimczik and Masiello 2007; DeLuca and Aplet 2008). Black C has generally been characterized as a comparatively stable form of C that can represent a major C sink, making up 5%–40% of total soil organic C when it becomes an integrated part of the soil matrix (Goldberg 1985; Czimczik and Masiello 2007; DeLuca and Aplet 2008; Liang et al. 2008).

Although total soil C can represent a relatively large fraction of total ecosystem C in longleaf ecosystems (Samuelson et al. 2014), little is known about fluxes of soil black C in frequently burned longleaf pine sites and its contribution to soil C pools. Ike (2010) reported that rates of soil black C accumulation were higher in frequently burned sites, but she also concluded that land use history has a larger influence on the overall size of the soil C pool than fire (see Chapter 7). Gonzalez-Benecke et al. (2015) reported that black C made up < 5% of soil organic C in longleaf pine stands and suggested that new inputs of black C from prescribed burning are small. However, the suggestion that black C fluxes and pools can be accurately estimated from shallow (often < 60 cm) surface soil analysis is based on several assumptions that have not been adequately supported by field studies. For example, the assumption that soil mixing in longleaf pine forests is unimportant is questionable based on the large number of burrowing species—such as gopher tortoise (*Gopherus polyphemus*), pocket gophers (*Geomys pinetis*), and ants—that characterize wildlife diversity in these systems.

These studies indicate that the standing pool of black C in frequently burned longleaf pine forests is small. However, recent research suggests that some fractions of the soil black C pool are actually more soluble than previously thought and that a large proportion of black C can be rapidly mobilized and transported through soils to aquatic systems (Dittmar et al. 2012; Jaffe et al. 2013). Jaffe et al. (2013) reported that about 10% of dissolved organic C flowing into and out of rivers originated from soluble charcoal. How these fluxes factor into terrestrial C loss from prescribed fire is unknown, and many questions remain about the factors that affect the storage and movement of black C in ecosystems. Mobilization and transport of black C are particularly important in the sandy soils that characterize much of the longleaf pine range. These questions provide a blueprint for studying black C transport and transformation in throughfall, soils, wetlands, and streams in watersheds that are dominated by longleaf pine.

Carbon Accounting in Longleaf Pine

The third critical area of investigation needed is development of optimal assessment metrics to quantify the value of longleaf pine restoration in projects that might consider C offsets as a restoration goal. C accounting (measuring the value of C emissions mitigation programs, such as forest management projects, in terms of total C impact) differs markedly from basic C science. Whereas C science focuses on net stand-level C exchanges (NEP, NEE, and NECB), C accounting protocols can also account for C sequestered in wood products removed from the site and for a project's secondary effects such as increased harvesting in nearby forested stands. Perhaps more importantly, the net outcome (in terms of the value of C offsets) of projects using C accounting principles reflects how the project performs against a modeled baseline of C stocks that reflects current regional forest conditions.

In a hypothetical longleaf pine restoration project in southwestern Georgia, Remucal et al. (2013) applied a forest project protocol that had been developed by the Climate Action Reserve to address greenhouse gas emissions in California. Their results showed a net emission of CO_2 over a hypothetical 100-year project lifespan. Although they proposed many reasons for this outcome, the primary factor was that prior restoration activities at the study site had reduced stand C stocks far below the expected C stock baseline for the Southeast. These same restoration activities had been considered successful in terms of restoring ecosystem structure and function, but the resulting stand structure (with characteristic low basal area and an open canopy) deviated from the typical C stocks observed in other nearby forests. As discussed previously, high C stocks in southeastern forests are a reflection of past reforestation of agricultural land, promotion of heavily stocked and productive forests through intensive management, and fire suppression. This means that current baseline forests do not represent the pre-European landscape in which the longleaf pine savanna was the dominant land cover.

We therefore suggest that fire-maintained longleaf pine should generally be considered the baseline condition for much of the southeastern Coastal Plain and for parts of the Piedmont. Because of the historical extensive coverage by longleaf pine, all changes in land cover since European settlement—including those that have contributed to the region's role as a major C sink—should be viewed as a result of human disturbance. Because current C accounting practices fall short when applied to longleaf pine ecosystems, further consideration must be given to how baseline conditions are determined.

CHALLENGES IN MEASURING COUPLED CARBON AND WATER CYCLES

Trade-Offs between Carbon and Water

Effective stewardship of ecosystem services requires land managers to recognize the substantial trade-offs that exist among alternative future land management scenarios (Daily and Matson 2008; Lindenmayer, Hulvey, et al. 2012). This dilemma is particularly important for land managers who are trying to balance C sequestration and ET. Ideally, simple metrics based on easily measureable plant physiology parameters would be adequate to understand these trade-offs and make informed decisions. For example, many researchers and land managers have given consideration to optimizing trade-offs between NEE and ET by selecting plant species for C offset projects and biofuel production based on water-use efficiency (King et al. 2013).

However, comparing water-use efficiency (WUE) alone does not adequately address the impacts of high annual net ecosystem productivity and high ET on water yield (Vose et al. 2015). At both the tree and stand levels, plant sensitivity (or insensitivity) to drought, rooting depth, soil water partitioning among species, and the physical effects of plant canopies on interception fluxes all play a role in balancing NEE with ET. At the watershed scale, feedbacks among vegetation, climate, soils, and other aspects of ecosystem function can also affect water yield, but not in the same manner as would be expected if estimates were based on WUE alone (Ukkola et al. 2016). Although knowledge of WUE among dominant species is a valuable first step, total ecosystem ET and the variables that affect ET are more critical measurements because it is the total amount of water used that affects C-water trade-offs and water supply (Sun et al. 2011; Sun and Vose 2016). Thus, as with other ecosystem services, managing NEE/ET trade-offs requires a better understanding of the ecosystem processes and feedbacks that affect the balance between productivity and water use (Carpenter et al. 2009).

Challenges in Coupled Carbon and Water Modeling

Projecting long-term C and ET dynamics in longleaf pine ecosystems and alternate land cover types will require models that couple the C and water cycles and account for ecosystem responses to climate variability under different projected climatic regimes. Predicting short-term responses to moderate drought is generally straightforward, especially if forest structure remains unchanged. However, climatic dryness (potential ET divided by precipitation), terrain characteristics, land cover types, biomass, soils, and characteristics of dominant species all influence the potential impacts of droughts on forest ecosystems. This complexity poses challenges for predicting the impacts of drought on ecosystem processes.

One of the major limitations of physically based modeling approaches is that changes in vegetation structure (such as reduced leaf area or changing root distributions) and function (such as shifts to species with different mechanisms for regulating water use) that occur in response to severe drought are rarely explicitly incorporated into modeling frameworks (Powell et al. 2013; Luo et al. 2008; Tague et al. 2013). Quantifying these changes often requires direct empirical investigation. Lumped parameter ecosystem models that were designed to describe the effects of soil water on ecological processes (such as C cycling) often oversimplify soil water and nutrient movement.

However, modeling approaches that account for subsurface hydrologic connectivity suggest strong spatial controls on ecosystem processes (Hwang et al. 2009; Emanuel et al. 2010). More accurate model predictions of severe and longer-term drought impacts will require a coupling of hydrologic and ecosystem processes within a dynamic context that includes appropriate feedbacks (Law 2015). This is not a trivial expectation; it requires the linking of leaf-level physiology, whole-tree responses, root dynamics and soil water access, stand level responses, and physical hydrology (Tague et al. 2013) into complex models that are difficult to parameterize and calibrate over large spatial scales.

Net water and C cycling in forested landscapes also depends on the spatial variation and covariation of forest species, structure, terrain, and soil conditions. Because management activities that alter water balances in upland forests can influence water balance elsewhere, a modeling approach to coupled water and C cycling in longleaf pine-dominated areas needs to consider the net landscape-level cycling—particularly with respect to lateral redistribution of subsurface water—over and above the scale of individual stands. In longleaf pine-dominated areas, slopes are typically gentle and topoclimate is constant, but soil variations can be substantial (Mitchell et al. 2014). These local variations depend on the parent material of soils and groundwater depth, which can range from near surface to well below the rooting zone. Local groundwater circulation redistributes rainfall recharge from uplands to bottomlands, distributing water and nutrient subsidies to some areas and maintaining more mesic conditions—with the potential for higher ET and C sequestration—in other areas.

Landscape Models Coupling Carbon and Water

Several models have been designed to address these challenges for some combinations of C, water, and nutrients, but relatively few models simultaneously address C and water at scales that are large enough to be useful for complex, mixed land cover watersheds. One of the most useful models is the Regional Hydro-Ecological Simulation System (RHESSys) (Band et al. 1993; Tague and Band 2004). The RHESSys developers initially combined a stand level water and C cycling model, Biome-BGC (Running and Coughlan 1988; Running and Gower 1991) with a distributed hydrologic base using flow path routing methods—which were adapted from TOPMODEL (Beven and Kirkby 1979) or the Distributed Hydrology Soil Vegetation Model (Wigmosta et al. 1994)—and soil biogeochemistry adapted from CENTURY (Parton et al. 1987; Parton 1996). RHESSys couples water and C cycling by building a network of hydrologic flow paths among ecosystem patches to derive aboveground and belowground primary productivity and water use, as well as surface and subsurface flows. It produces a template that is useful for mapping the gradient of more xeric to mesic edaphic conditions, including long-term changes and patterns in soil organic C.

Structurally, RHESSys is set up as a nested hierarchy of ecosystem patches, hillslopes, and catchments. Within patches, multiple strata (such as species or plant functional groups) can be incorporated; water, C, and nitrogen cycling can be solved for each stratum; and interaction and competition for resources can be tracked. Bottomland or riparian conditions (higher soil water and soil organic C) do not need to be prescribed, but can evolve over varying time periods by the lateral redistribution of moisture and net effects on aboveground and belowground C cycling. RHESSys can incorporate input on shrub and herbaceous layers into canopy gap statistics to provide distributed radiation between canopy and forest floor (Song and Band 2004; Song et al. 2009), with mixed species composition influencing stomatal and aerodynamic conductance. Further, the different strata included within an ecosystem patch can incorporate different root depths, allowing the tracking of interaction and competition for soil water. Disturbances, in the form of fire or management, can be incorporated by altering drainage flow paths or by scheduling events that alter the state variables used to describe canopy and soil conditions, or by altering drainage flow paths. Forest floor litter layers are maintained by C and water-mass balance, providing both total biomass and water content (which can interface with fire models).

Soil condition data must be at the scale of hydrologic flow paths because edaphic gradients can serve as strong drivers of forest growth and exchanges of C, water, and nutrients. However, these scales are often below the resolution of soil mapping—which is typically limited to a specific scale of mappable soil bodies and incorporates multiple inclusions (different soil series and phases) within a polygon. The RHESSys framework uses a knowledge-based method of inferring higher resolution soil properties that reflect the resolution of the available terrain data. If adequate terrain data are available, the Soil Landscape Inference Model (SoLIM) (Zhu et al. 1996, 2010) can be used for inferring spatial variations of critical soil properties in low-relief landscapes; these data are now becoming widely available in the Southeast through state-level LiDAR (light detection and ranging) mapping. Mapping canopy conditions and inferring soil variation at these scales would be required before the landscape-level patterns that characterize and determine edaphic gradients can be incorporated.

Other Scaling Challenges

Importance of Accurate Land Cover Estimates

Landscape-level models, such as RHESSys, rely on accurate land cover data for reliable predictions of NEE or ET. One reason that the potential of longleaf pine to improve water yield may not have been more thoughtfully considered in the past is the general failure to differentiate longleaf pine from other pine-dominated systems at the landscape scale. Much of what we know about pine ET in the Southeast comes from studies of slash pine, loblolly pine (*P. taeda*), and eastern white pine (*P. strobus*). Although these pines generally have higher WUE than hardwoods, they also tend to have higher annual ET rates because of their high leaf-level transpiration rates, year-round transpiration, and high winter interception resulting from the evergreen leaf habit and high stand density (Swank and Miner 1968; Swank and Douglass 1974; Ford et al. 2011; McLaughlin et al. 2013; Novick et al. 2015). However, these generalizations about high leaf-level ET and stand density do not apply to restored longleaf pine, suggesting that an accurate differentiation between longleaf pine cover and other pine land cover is needed.

Using spectral profiles to differentiate among pines is considerably more difficult than distinguishing between pines and hardwoods (van Aardt 2000). Thus, when stand-level ET is scaled to the watershed using remotely sensed data, all pine cover is generally lumped into a single category and potential differences in ET between longleaf pine and other pine species cannot be quantified. In an attempt to separate longleaf pine from loblolly pine, Nieminen et al. (2014) reported slight differences in spectral signatures that were collected using images from the DigitalGlobe WorldView-2 satellite; however, these differences were influenced by season and by the substantial differences in subcanopy vegetation that characterize the stands dominated by the two species. Alternately, Martin et al. (2013) used aerial photography to distinguish planted pine from naturally regenerated forest, but they could not visually distinguish among the pine species. To minimize the time involved in visually assessing land cover for individual photographs, they relied on a subset of available photographs. Although their results are useful, the relatively small geographic area represented could introduce errors into land cover estimates at larger scales. If better methods for distinguishing longleaf pine from other pines could be developed, then more accurate estimates of longleaf pine land cover could be incorporated into watershed scale ET estimates.

Model Validation

Models that link C and water can be useful, but the ability to validate modeled results with reliable independent estimates would add considerable value and veracity to modeled results. However, validating models to determine how land cover change and land management actually affect streamflow in longleaf pine restoration areas is difficult. Unlike controlled watershed experiments—which rely on small, confined, and well-defined catchments—much of the southeastern Coastal Plain does not lend itself to the water balance measurements typically used to balance basin water budgets (calculating ET by subtracting water yield from precipitation). For example, in much of southwestern Georgia and most of northern Florida, significant interactions between groundwater and surface water complicate efforts to study interactions between ET and water yield. In much of the longleaf pine range, reducing ET by managing land cover might increase either stream runoff or groundwater recharge (or both), but our understanding of groundwater and surface water interactions in these systems is incomplete (Rugel et al. 2012). Addressing these challenges will require an interdisciplinary approach and inclusion of experts—in soil hydrology, surface water hydrology, and groundwater hydrology—who work in concert with forest ecologists and landscape modelers.

CAN WATER AND CARBON POLICY PLAY A ROLE IN RESTORING LONGLEAF PINE?

Numerous strategies have been proposed for managing water scarcity in the Southeast. The emerging hypothesis that longleaf pine restoration could contribute to increased water yield, coupled with a growing policy focus on water-scarcity mitigation strategies, suggests that longleaf pine restoration could play a new and important role in the development of "water-wise" conservation easements. Despite this potential opportunity, the extent of restoration could be limited by several factors, including a current policy emphasis on C sequestration, public reluctance to accept frequent fire, and the long-term commitment required for successful restoration (see Chapter 3). Ultimately, the greatest challenge to expanding restoration at scales large enough to have a measureable effect on regional water scarcity may simply be that alternate land uses can generate substantially more income. Effective policies to encourage restoration will be needed to overcome these income and price barriers.

Unlike much of the forested land in the Southern Appalachian Mountains and in western states, forests in the Coastal Plain and Piedmont are primarily controlled by private landowners (Conner and Hartsell 2002). Landowner choices reflect the valuations placed on various land uses and on perceptions of risk. In such a landscape, the variety of land uses often reflects differences in site productivity and comparative advantage as well as variations in the nonmonetary benefits that owners expect from their holdings. Land use in the Southeast has shifted substantially over several decades as crop agriculture has generally trended downward—and is now concentrated in a few areas (such as Florida, the Mississippi Delta) or elsewhere in the United States (Wear 2013). Agricultural commodity prices can largely explain the shift in land uses, with prices for major crops trending downward during the 1980s and 1990s, reaching a nadir and then trending upward over the past decade, and remaining strong in recent years. Evidence from various data sources—including the National Resources Inventory (USDA 2015) and U.S. Forest Service survey results—indicates a concomitant shifting of agricultural land area to forest uses and some increase in forest land area shifting to agricultural uses. These recent price dynamics do not represent a projection of future price paths but they do indicate that in rural areas—where land use changes may be dominated by demands for developed land—the area deemed suitable for forest management, and thus for longleaf pine restoration, is influenced by the condition of competing agricultural markets.

Competition among wood products also influences a landowner's forest management choices. Since the Great Recession (2007–2009), demand and prices for sawtimber have been substantially lower than historical averages. In comparison, pine pulpwood returns have remained strong and even increased somewhat, potentially explaining the substantial increase in loblolly pine plantations in the Southeast. This reflects a combination of cyclical factors and long-term trends in demand (Wear et al. 2016). However, it also highlights higher returns from traditional intensive pine management and much less variance in pulpwood returns, at least in the short term; both of these factors favor short-rotation pine management over either less intensive forest management or longleaf pine restoration (Wear et al. 2016).

Because agricultural commodity prices, timber commodity prices, and price variance all play into land use decisions, they need to be addressed in the design of policy incentives. Conservation-oriented tax incentives influence land use choices for owners of marginal lands or for owners who are more interested in conservation than maximizing income generation. But with few exceptions, current tax incentive programs are not designed to emphasize low-density forests and frequent applications of prescribed fire. Although they offer considerable support for longleaf pine restoration to improve wildlife habitat, these incentive programs would have more value if they included offsets to forest water use. Such programs, however, could conflict with current or future C policy that may or may not favor longleaf pine restoration. Ultimately, land use portfolios represent a combination of uses that collectively attempt to hedge against future risks. Longleaf pine, even where it does not define the highest return to management, could be a part of the portfolio given its comparatively low risk and high value profile. Adding additional financial benefits through tax incentives focused on water-based ecosystem services (such as higher streamflow) could further increase that value.

For water valuation programs to be successful, scientists and policy makers will need to balance C sequestration goals with water supply needs, especially in areas that are (or could be) affected by water scarcity. This shift in policy would require acknowledgement that some natural and restored ecosystems will likely have lower C sequestration—at least in the short term—than the rates observed over the past century. Such a shift would also suggest that rather than focusing on C sequestration or any single ecosystem service, policy makers may need to focus more on the overall suite of services, including ecosystem resilience. Of course, this type of "bundling" may be optimal for some locations—depending on local hydrology, soil characteristics, or land use history—but specialization may serve better in others, emphasizing the need for better scientific assessment in policy design.

SUMMARY

Numerous successes in improving ecosystem function and increasing the availability of ecosystem services in the Southeast can be attributed to the restoration of longleaf pine. The large majority of these successes have been measured in relation to wildlife conservation, with additional value realized in benefits to human health (Gleim et al. 2014). Even with these successes and continued efforts to restore longleaf pine, more information is needed to understand fire-managed longleaf pine restoration and appreciate its value in addressing regional environmental issues such as water scarcity and global environmental issues such as climate change mitigation. Our review suggests that pursuing such restorations would likely contribute to water scarcity mitigation while also contributing modestly and sustainably to long-term C sequestration. However, these benefits come at the expense of short-term C sequestration and would require refinement of policies that currently use short-term metrics (such as NEE) to evaluate C sequestration potential. Otherwise, these benefits are highly complementary to established restoration goals and thus represent added returns on investments in restoration projects.

We have identified several critical needs and next steps for improving the metrics used to quantify the effects of longleaf restoration on bundled ecosystem services. These include additional measurements of NEE and evapotranspiration across a wider geographic range, continued support for existing studies that collect data on long-term NEE and evapotranspiration, improvements in modeling, and better coordination and synthesis of research across the region. Addressing these needs and using subsequent findings to inform policy would provide one avenue for increasing restoration opportunities while moving toward water sustainability in the Southeast.

Finally, we suggest better mechanisms for communicating the potential benefits of longleaf restoration to land managers, policy makers, and other stakeholders—especially those concerned with mitigating water scarcity.

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