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MANAGING FORESTS FOR INCREASED REGIONAL WATER YIELD IN THE SOUTHEASTERN U.S. COASTAL PLAIN[1]

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ABSTRACT: With growing populations fueling increased groundwater abstraction and forecasts of greater water scarcity in the southeastern United States, identifying land management strategies that enhance water availability will be vital to maintaining hydrologic resources and protecting natural systems. Management of forested uplands for lower basal area, currently a priority for habitat improvement on public lands, may also increase water yield through decreased evapotranspiration (ET). To explore this hypothesis, we synthesized studies of precipitation and ET in coastal plain pine stands to develop a statistical model of water yield as a function of management strategy, stand structure, and ecosystem water use. This model allowed us to estimate changes in water yield in response to varying management strategies across spatial scales from the individual stand to a regional watershed. Results suggest that slash pine stands managed at lower basal areas can have up to 64% more cumulative water yield over a 25-year rotation compared to systems managed for high-density timber production, with the greatest increases in stands also managed for recurrent understory fire. Although there are important uncertainties in the magnitude of additional water yield and its final destination (i.e., surface water bodies *vs.* groundwater), this analysis highlights the potential for management activities on public and private timber lands to partially offset increasing demand on surface and groundwater resources.

(KEY TERMS: water use; water yield; groundwater; restoration; forest management; pine plantation; evapotranspiration; statistical model.)

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INTRODUCTION

The southeastern coastal plain of the United States (U.S.) was historically characterized by extensive uneven-aged pine stands with widely spaced trees and short (e.g., 2-3 years) fire return frequency that reduced fuel load and understory biomass (Abrahamson and Hartnett, 1990). With the significant loss of this ecosystem to development and plantation forest production, many local, state, and federal agencies have recently focused efforts on acquiring lands previously under intensive silvicultural management (i.e., high basal area and tree density) for restoration to this historic state (Freeman and Jose, 2009). Whereas the perceived benefits of upland restoration and management are typically limited to wildfire prevention and habitat improvements (e.g., increased

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understory biodiversity and improved habitat suitability for rare and endangered species), restoration and management practices that reduce biomass, such as selective thinning and prescribed fire, may also reduce ecosystem water use (Edwards and Troendle, 2012), increasing water yield to local and regional surface and groundwater resources. Given increasing demands on already overtaxed water resources (Sun *et al.*, 2008; SJRWMD, 2012) and predictions of increased water scarcity in the southeast (Karl *et al.*, 2009), forest management for reduced biomass may also prove to be a useful element in comprehensive water conservation strategies and supply planning.

The net water yield of a system is defined as the difference between precipitation (PPT) and evapotranspiration (ET) (Anderson *et al.*, 1976), and this yield supplies both surface and groundwater resources. In the southeastern U.S., approximately 70% of rainfall is lost to ET (Hanson, 1991), whereas ET losses of over 90% have been reported for mature, high-intensity pine plantations in Florida (Gholz and Clark, 2002) and North Carolina (Sun *et al.*, 2010). Since ET dominates ecosystem water losses, small reductions in ET can have a large impact on water yield. For example, modestly reducing ET/PPT from 90 to 80% *doubles* the water yield (i.e., from 10 to 20%). Relative to intensively managed pine plantations, naturally regenerated pine stands in Florida have been shown to have lower values of ET/PPT, ranging 75-85% (Powell *et al.*, 2005; Bracho *et al.*, 2008), suggesting a potential increase in water yields from uplands restored to — and maintained at — lower stand-level basal and leaf areas. It follows that upland management to maintain reduced biomass can result in increased water subsidies to surface water bodies (wetlands, lakes, and streams) and groundwater resources.

Numerous studies have convincingly shown that clear-cut timber harvest increases streamflow (e.g., see reviews in Bosch and Hewlett, 1982; Jackson *et al.*, 2004; Edwards and Troendle, 2012). Water table rise following harvest (i.e., "watering up") (Dube *et al.*, 1995) has also been documented, particularly in the southeastern coastal plain (Williams and Lipscomb, 1981; Sun *et al.*, 2001; Bliss and Comerford, 2002; Xu *et al.*, 2002; Amatya *et al.*, 2006b; Lu *et al.*, 2009). These hydrologic impacts are temporary, however, with water use in revegetated stands typically recovering within 10 years (Riekerk, 1989; Hornbeck *et al.*, 1993; Sun *et al.*, 1998). In fact, water use in revegetated stands can exceed preharvest water use due to stimulated revegetation via fertilization, weed control, increased stock density, and site preparation (Hornbeck *et al.*, 1993; Bliss and Comerford, 2002). While these investigations unequivocally show the short-term hydrologic implications of dramatically reduced forest biomass, we hypothesize that management strategies that consistently maintain pine stands at lower basal areas — whether implemented on public lands or pine plantations — have a more subtle (but sustained) impact on regional water yield.

Although current groundwater models consider land use when calculating recharge (e.g., Harbaugh, 2005), they generally apply lumped parameters for groups of land use and soil classes (e.g., Batelaan *et al.*, 2003). Thus, pine forests of all types (i.e., plantations in various stages of rotation, naturally regenerated pinelands on public and private lands; thinned and fire-managed pine systems on local, state, and federal land) are grouped into a single land-use category; the effects of changing forest structure on the water yield are not considered. Predicting the effects of specific forest management strategies on changes in water yield requires a model that quantifies relationships between management, stand structure, and water yield in a specific forest type and region over a typical timber rotation. In this study, we synthesized the existing literature to develop such a model for slash pine (*Pinus elliottii* Engelm.) stands in Florida over a 25-year rotation that includes all phases of the silvicultural cycle, including clear cutting and replanting. This approach allowed us to explore the timing and magnitude of management-induced water subsidies as a function of forest stand structure and management and provided a means for comparing net water yield from typical silvicultural systems compared with pine stands managed for lower basal area. This study adds to the current practice of water yield modeling by considering water use in pine uplands under different management strategies as "non-point source" consumption and demonstrating how changes in management within a specific land use can have substantial cumulative impacts on regional water supply.

MATERIALS AND METHODS

Stand Structure and ET

Peer-reviewed publications were surveyed for studies documenting ET estimates from forests with varying structure (age, height, density, basal area, and leaf area index). The review was restricted to investigations conducted in coastal plain pine stands of the Southeast U.S. and included both naturally regenerated stands managed for low basal area and planted pine plantations intensively managed for high basal area wood production. Methods used to determine ET in the reviewed studies included direct measurements (weighing lysimeters, eddy correlation), water balance methods that accounted for changes in watershed storage, and simulation models. Studies that estimated ET simply as the difference between measured rainfall and watershed drainage were excluded to avoid errors introduced from changes in watershed storage (i.e., groundwater and/or soil water storage). Studies reported measured annual ET and annual precipitation, which were averaged over each study's duration. Annual ET was indexed to annual precipitation, yielding a relative measure of ecosystem water use for each study site (i.e., the ratio of ET to precipitation; ET/PPT). The remaining rainfall was assumed to represent ecosystem water yield (i.e., 1 — ET/PPT). No assumptions were made about the specific fate (i.e., delivery to surface or groundwater) of this water yield.

To develop a statistical model of pine stand ecosystem water use and yield based on stand structure and management, we first explored relationships between ET/PPT and tree height, tree density, tree basal area, and leaf area index (LAI). To limit influences of large climatic variability and species-specific water use efficiencies, only studies of slash pine stands in Florida were used in model development. All-sided LAI measurements included direct methods (e.g., harvest methods, litterfall) and indirect methods (e.g., light penetration methods and allometric equations) calibrated with harvesting. Projected LAI rather than all-sided was reported in one loblolly study (Sun *et al.*, 2010); these data were converted into all-sided LAI using a conversion factor specific to loblolly stands in the region (Vose and Allen, 1988). Reported LAI values were measured in late summer through late fall.

Since LAI measurement methods can include potential error (Gower *et al.*, 1999), a Type-II ranged major axis (RMA) regression was used to determine the relationship between ET/PPT and LAI (to avoid implicitly assuming high confidence in the independent variable). Measurement errors for other stand metrics (basal area, height, and density) are much lower than error in LAI, supporting the use of Type-I ordinary least squares (OLS) regression for these relationships (i.e., Legendre and Legendre, 1998). Of the four stand attributes, LAI was the best predictor of water use (i.e., ET/PPT); however, it is not as frequently reported as other stand attributes (e.g., stand age and tree basal area). Therefore, further relationships to relate LAI to basal area and stand age were explored using LAI and basal area data from 26 slash pine-dominated stands in Florida (Gholz and Fisher, 1982; Gholz *et al.*, 1991; Gholz and Clark, 2002; Powell *et al.*, 2005); this larger dataset included studies that reported stand age, basal area, and LAI, but did not necessarily report ET rates.

Water Yield Potential of Pine Stands Under Different Management

Using these relationships, we compared annual and cumulative water yields from planted pine plantation (PP) over a full 25-year rotation with those from stands managed for constant but low basal area (LBA) over the same period. Stands with constant basal areas ranging from 8-14 m^2/ha (LBA-8, LBA-10, LBA-12, LBA-14) were simulated, which comprise the range of restoration targets for naturally regenerated pine flatwoods (e.g., Freeman and Jose, 2009; Mallet, 2009; Coates and Lewis, 2010; Outcalt and Brockway, 2010). The LBA system represents a mature stand removed from industrial forest production operations (i.e., clear cutting and stimulated regeneration) and where periodic selective thinning is implemented to maintain low basal area.

Water yield per unit area [mm] from each management strategy on an annual basis was calculated by

$$\text{Water Yield} = \left(1 - \frac{\text{ET}}{\text{PPT}}\right) * \text{MAP} \qquad (1)$$

where ET/PPT [-] is predicted with LAI, and MAP is mean annual precipitation [mm] (assumed to be 1,300 mm based on long-term regional meteorology [NOAA, 2012]). Fitted relationships between ET/PPT and LAI and between LAI and stand age were coupled with Equation (1) to estimate annual water yield of a PP plantation during each year of a 25-year rotation (beginning with clear cutting). Annual water yield was estimated for LBA stands using regressions between ET/PPT and LAI and between LAI and basal area. Cumulative water yield (CWY) from each scenario was calculated by summing annual water yields.

We quantified the uncertainty in modeled regression parameters and propagated it through the empirical model using a bootstrapping method. Confidence intervals (CIs) for regression parameters relating LAI to ET/PPT, basal area to LAI, and stand age to LAI were calculated using SigmaPlot (Systat Software, San Jose, California). We then randomly sampled input regression parameters from within the 95% CIs, assuming a standard normal distribution to generate 1,000 model realizations for each PP and LBA management scenario, subject to the practical constraints of $ET/PPT \leq 1.0$ and $LAI \geq 0$. The results from each realization were used to calculate a range (i.e., mean ± SD) of CWY from each management scenario and differences between them (ΔCWY). All regression parameters were sampled independently within and between realizations; however, *changes* in CWY realized by converting from PP to LBA management were computed *within* each model realization such that differences between scenarios were calculated using the same parameterization of the LAI-to-ET/PPT relationship.

Simulating Fire

Reestablishing recurrent fire for habitat improvement and wildfire prevention is a management strategy that is often implemented in conjunction with maintaining low basal area. The implications of fire on forested watershed water yield have been explored in several studies (Helvey, 1980; Bosch and Hewlett, 1982; Scott, 1993), but with a focus primarily on intense wildfires. Less is known about the water yield implications of prescribed understory fires that generally do not reach the canopy (Edwards and Troendle, 2012). It has been proposed that forests with different tree densities maintain similar ET rates relative to climatic drivers by increasing the understory contribution to ecosystem ET with decreasing canopy LAI (Roberts, 1983; Phillips and Oren, 2001). This increased understory ET may partially offset reductions in water use from converting PP stands into LBA stands (Powell *et al.*, 2005). Prescribed fire, however, is typically conducted in LBA stands, periodically removing understory vegetation and likely reducing ecosystem ET while the understory vegetation recovers between burns.

To accurately represent the water yield impacts of frequent understory-clearing burns in forests with different management strategies requires an understanding of the partitioning of LAI between understory and canopy across a range of forest structures. For example, the proportion of total LAI contributed by the understory (which would be eliminated or reduced by frequent, low-intensity fire) changes with stand basal area; it is lowest in stands with high tree basal area (due to shading by the canopy) and highest in stands with low basal area. Although data were not available to develop this relationship across a full range of basal areas, several investigations partitioning transpiration among understory and canopy species allow us to draw inference about the likely effects of prescribed understory fires. For example, Powell *et al.* (2005) separately measured ET of the subcanopy and canopy of a naturally regenerated slash pine stand that had not been burned for five years. Total LAI of the system was 4.7 m^2/m^2, of which understory vegetation contributed approximately 23%, corresponding to 45% of the total ET flux (Table 1). Similarly, Oren *et al.* (1998) found that understory vegetation contributed nearly 27% of total ET flux in a 13-year-old loblolly stand (canopy LAI = 3.0) and Granier *et al.* (1990) found 30% of ET flux to be attributed to the understory in a maritime pine system (canopy LAI = 2.3).

These studies suggest that frequent burning has potential implications for ecosystem ET and water yield. To simulate this effect in our model of water yield in LBA stands, we used the LAI partitioning data from Powell *et al.* (2005) to simulate a three-year fire return frequency by eliminating understory LAI (23% of total LAI) in year 1 of the fire cycle and assuming a linear recovery rate (i.e., 50 and 100% understory LAI recovery in years 2 and 3 of the recurrent three year cycle, respectively). Simulated fire represented prescribed burns (typically implemented every 2-5 years in southern pine forest management) (Carter and Foster, 2004) and was thus assumed to be spatially uniform (i.e., no patchiness). While Powell *et al.* (2005) found 23% of total LAI was contributed by understory in a stand with basal area of 18 m^2/ha, we apply this reduction in stands with lower basal areas (14 m^2/ha); because understory LAI and ET are likely greater in these lower basal area stands (Roberts, 1983; Phillips and Oren, 2001), the impacts of understory-clearing fire would be even larger, and this approach likely provides a conservative estimate of the increased water yield due to regularly prescribed understory fire.

Estimating Water Yield at Local and Regional Scales

To scale-up the potential implications of forest management on water yield, we simulated effects from management strategies (basal area reductions and prescribed fire) using: (1) forest inventory data from specific PP stands to evaluate local-scale effects; and (2) spatial data on the extent of PP lands within Flagler County and St. Johns Water Management District (SJRWMD) to predict regional effects. At the local scale, we used site-specific basal area and stand area data for 15 PP stands (total area = 1,700 ha) on Rayonier's Hargrove Pasture parcel in Flagler County, Florida (Figure 1). These data were used along with the developed relationship between LAI and basal area, Equation (1), and regional MAP to estimate existing annual water yield from each stand, as well as predicted annual water yields following basal area reductions (i.e., LBA-8, LBA-10, LBA-12, LBA-14), with and without fire.

At the regional scale, we used empirical relationships between LAI and stand age to simulate water yield subsidies realized from converting regional PP lands into LBA management over a 25-year rotation. Using ArcGIS and publicly available Florida land-use/land-cover classification (FLUCCS) data from 2009 (available at www.sjrwmd.com/tools GISdata/),

TABLE 1. Studies Investigating Pine Stand Structure and Water Use (Including Annual Evapotranspiration, ET, and Annual Precipitation, PPT) in the Southeastern Coastal Plain.

Study	Loc.	Land Use	Dominant Sp.	Age (years)	Tree Ht (m)	Density (trees/ha)	LAI (m^2/m^2)	BA (m^2/ha)	ET (mm/yr)	PPT (mm/yr)	ET/ PPT	Method
Knowles (1996)	Florida	PP	Slash	5	1.5	3,000	2.3		813	1,270	0.64	EC
Ewel and Gholz (1991)	Florida	PP	Slash	29	17.0	1,150	6.5	27.2	1,168	1,187	0.98	MS
Liu *et al.* (1998)	Florida	PP	Slash	30			5.0		1,020	1,276	0.80	EC+MS
Liu *et al.* (1998)	Florida	PP	Slash	30			6.0		1,109	1,276	0.87	EC+MS
Liu *et al.* (1998)	Florida	PP	Slash	30			7.0		1,178	1,276	0.92	EC+MS
Riekerk (1985)	Florida	PP	Slash	5		1,000			1,006	1,254	0.80	LM
Powell *et al.* (2005)	Florida	NR	Slash, Longleaf	60	22.0	325	4.7	18.0	754	884	0.85	EC
Overstory							3.6		415	884	0.47	EC
Understory							1.1		339	884	0.38	EC
Bidlake *et al.* (1996)	Florida	NR	Slash		7.8	96	<20% Canopy coverage		1,060	1,440	0.74	EC
Sumner (2001)	Florida	PP	Slash, Cypress	30					1,048	1,245	0.84	EC
Gholz and Clark (2002)	Florida	PP	Slash	1	1.0	3,000	3.0		959	1,127	0.85	EC
Gholz and Clark (2002)	Florida	PP	Slash	10	11.0	2,075	5.1	15.7	1,058	1,062	1.00	EC
Gholz and Clark (2002)	Florida	PP	Slash	25	19.2	1,184	6.5	31.4	1,194	1,288	0.93	EC
Liu (1996)	Florida	PP	Slash	30	17.5	544	3.7	14.2	800	1,333	0.60	EC+MS
Amatya *et al.* (1996)	NC	PP	Loblolly	17			9.0	16.1	1,060	1,515	0.70	WB
Sun *et al.* (2010)	NC	PP	Loblolly	5		1,040			838	1,274	0.66	EC
Sun *et al.* (2010)	NC	PP	Loblolly	14	12.9	1,660	11.0	25.0	1,087	1,238	0.88	EC

Notes: PP, Planted pine; NR, naturally regenerated; LAI, Leaf area index; BA, basal area; EC, eddy covariance; MS, model simulation; LM, lysimeter; WB, water balance. All-sided LAI for Sun *et al.* (2010) was converted from reported projected LAI using a conversion factor of 2.68 (Vose and Allen, 1988).

we calculated the current extent of all publicly and privately owned PP lands within Flagler County and the SJRWMD, one of Florida's five water management districts (Figure 1) and an area with intensifying groundwater resource depletion and growing water supply challenges. Using these areas and regional MAP, we compared regional CWY of PP over a full rotation with LBA scenarios (with and without fire). The range of likely net water yield increases (or decreases) resulting from different management strategies was calculated to determine the hydrologic implications of forest management within a large watershed.

RESULTS

Stand Structure and ET

Table 1 summarizes stand structure and annual ET/PPT data from 11 studies conducted in PP plantations and naturally regenerated (NR), secondary growth pine stands throughout the southeastern coastal plain. More data were available for Florida slash pine-dominated systems (Table 1); we focused on these in exploring region-specific relationships between ET/PPT and stand LAI, stand basal area, average tree height, and stand density. In these slash pine stands, LAI was the best predictor of stand ET/PPT (R^2 = 0.53; Figure 2) as expected since leaf area is the exchange surface area for water, energy, and gas fluxes and thus regulates productivity and water use (Vose *et al.*, 1994). The broad 95% CIs around this best fit line are indicative of the relatively small number of studies used to create this relationship (n = 10), which is a source of model uncertainty, explored in detail below. Although LAI is correlated with basal area (e.g., Vose *et al.*, 1994), the regression between ET/PPT and basal area was weaker (R^2 = 0.26). The relationships between ET/PPT and both tree height and stand density were poor (R^2 = 0.01 and < 0.01, respectively), because basal area and LAI both vary across stands of equal heights and densities.

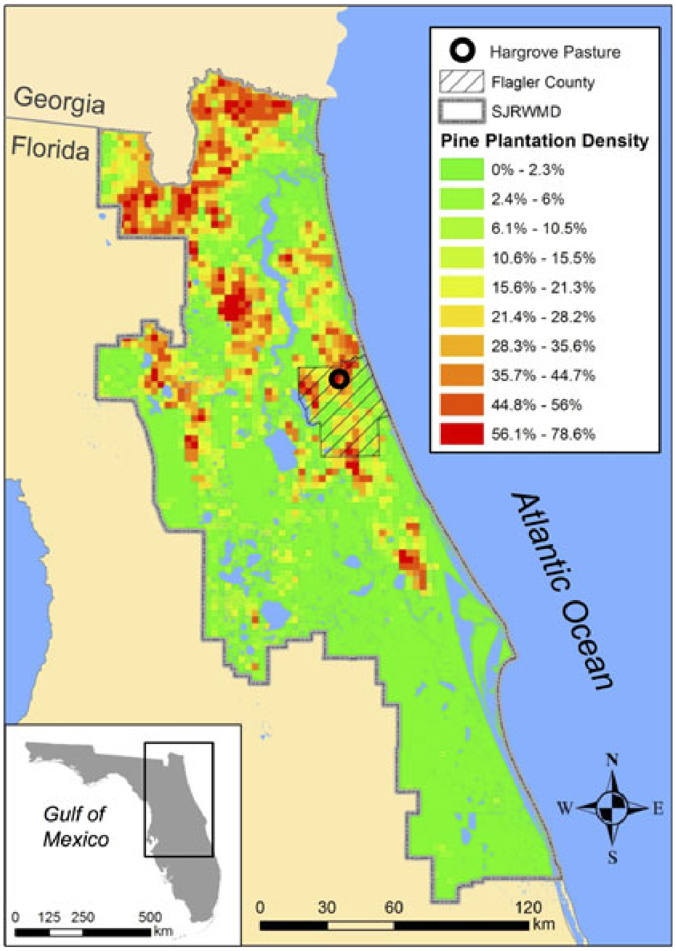

FIGURE 1. Distribution and Density of Pine Plantation Within the St. Johns Water Management District (SJRWMD) in Northeast Florida. The area contains over 300,000 ha of pine plantation, of which ca. 65,000 ha are publicly owned (local, state, and federal).

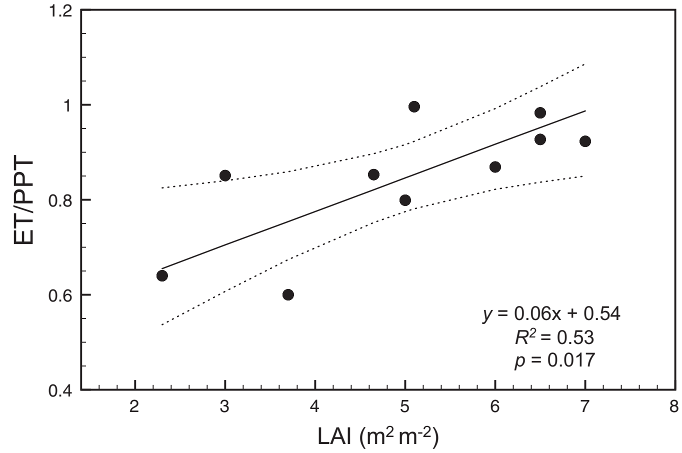

FIGURE 2. Ratio of Evapotranspiration to Precipitation (ET/PPT) in Florida Slash Pine Stands as a Function of Stand Leaf Area Index (LAI).

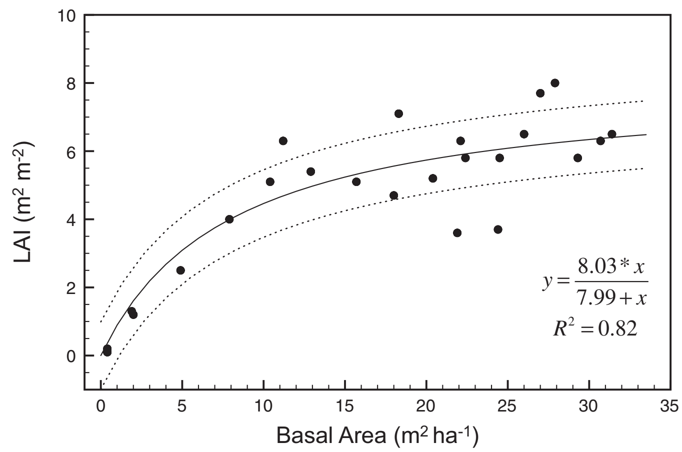

FIGURE 3. Stand Leaf Area Index (LAI) as a Function of Stand Basal Area for Florida Slash Pine Stands.

LAI, Basal Area, and Stand Age

A larger dataset than presented in Table 1 (including studies that did not report ET) was used to construct relationships between LAI and basal area and between LAI and stand age. A Michaelis-Menten (MM) model yielded a strong fit between basal area and LAI (R^2 = 0.83; Figure 3), providing a function to couple with the relationship in Figure 2 to estimate slash pine ecosystem water yield with variation in stand basal area. To estimate water use and yield as a function of time in growing PP stands, a direct relationship between stand age and LAI was also investigated and similarly yielded a MM model, though with a weaker fit (R^2 = 0.50; data not shown). Restricting this relationship to managed pine plantations strengthened the fit (R^2 = 0.56; data not shown) and suggested that plantation pine LAI stabilizes by approximately 14 years since planting, as previously documented by Gholz and Fisher (1982) and Vose *et al.* (1994). Considering this stabilization in LAI, we separated the stand age *vs.* LAI relationship into a biphasic model with a positive linear regression for the first 13 years (R^2 = 0.77) and a constant LAI of 6.5 m^2/m^2 for subsequent years (mean ± SD LAI of stands ≥14 years = 6.5 ± 0.87 m^2/m^2) (PP-High, dashed line in Figure 4). This model allowed us to predict LAI, and thus water use, of PP stands directly as function of stand age without fitting a third regression between stand age and basal area, for which few data were available. Uncertainty in the two phases of the biphasic regression between age and LAI was considered independently (i.e., 95% CIs in Figure 4).

Canopy and total LAI measurements (closed and open circles in Figure 4, respectively) were similar

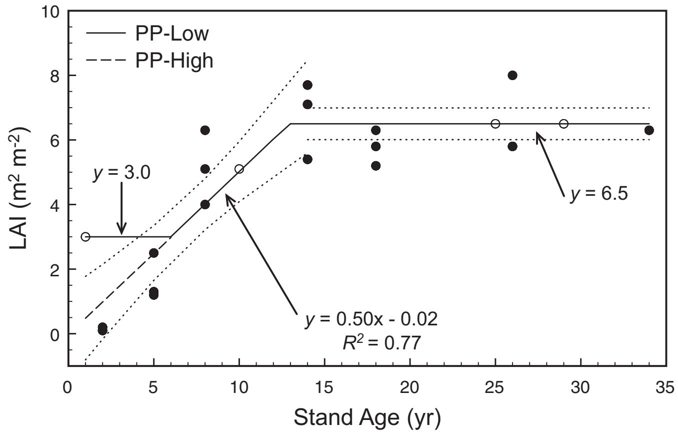

FIGURE 4. Stand Leaf Area Index (LAI) as a Function of Stand Age for Florida Slash Pine Plantations. Closed circles represent canopy LAI, and open circles represent total (canopy and understory) LAI. The model represented by the dashed line uses the given linear regression to predict LAI as a function of stand age from planting through year 14 and represents a (relatively) higher water yield system (PP-High). The solid line assumes a constant LAI value of 3.0 from planting through year 6 and uses the linear regression from year 6 through year 14, representing a lower water yield system (PP-Low). Both models assume a constant LAI value of 6.5 ± 0.87 m^2/m^2 from year 14 onward. Note that PP-High and PP-Low overlap for stand age ≥ 6 years.

when stand age was greater than ca. 8 years, suggesting a negligible effect of understory transpiration in mature plantation stands; however, the proportion of understory foliage relative to total stand foliage can be dominant within the first several years following clear cutting (Gholz and Fisher, 1982). Comparing canopy LAI values of young stands (<6 years old) to the only available total LAI measurement for a young (1-year-old) PP stand (Gholz and Clark, 2002) suggests that understory LAI dominates total LAI in young stands. This was also shown by Sampson *et al.* (2011) for loblolly stands <4 years old, and indicates that total LAI is likely higher than the value predicted by the linear regression for PP-High in Figure 4. This suggests that the relationship predicting total LAI of PP using stand age (PP-High, Figure 4) may underestimate LAI in young stands, leading to *underestimates* of ET/PPT and *overestimates* of water yield. To bound this uncertainty, a second estimate of the stand age-LAI relationship was constructed using a higher, constant LAI value of 3.0 m^2/m^2 (Gholz and Clark, 2002) assigned to stands ≤6 years, representing a PP system with an overall *higher* water use and therefore *lower* water yield (PP-Low, solid line in Figure 4). When assessing the uncertainty around modeled water yield from the PP-Low scenario, we assumed a constant value of LAI = 3.0 for stand age ≤6 years since we could not build a stochastic input distribution around this single data point.

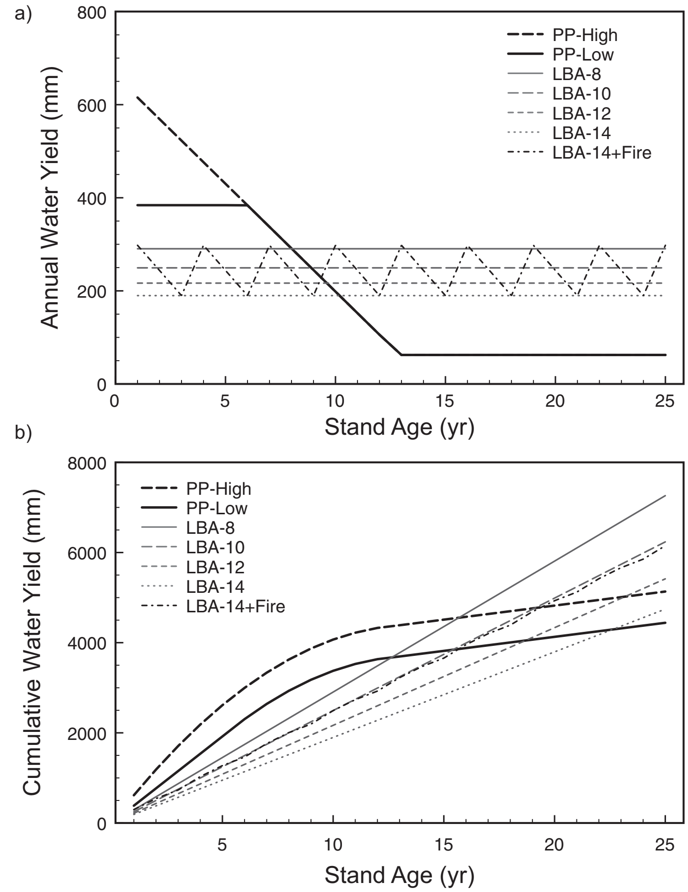

FIGURE 5. Simulated Annual (a) and Cumulative (b) Water Yield from Planted Pine (PP) Plantation, Managed Systems Maintained at Low Basal Areas of 8, 10, 12, and 14 m^2/ha (LBA-8, LBA-10, LBA-12, and LBA-14), and LBA Management with the Addition of Recurrent Fire to Clear Understory Vegetation (LBA-14+Fire). PP-High and PP-Low represent high and low estimates of PP water yield based on assumptions about leaf area index and water use of young PP. Note that PP-High and PP-Low in panel (a) overlap for stand age ≥ 6 yrs.

Water Yield of Pine Stands Under Different Management

Figure 5 illustrates modeled annual (a) and cumulative (b) water yield in simulated PP and LBA stands using Equation (1) and best fit regression parameters from the relationships relating stand attributes and ET/PPT. Reduced biomass and LAI following clear-cut yields lower water use and higher annual water yield in the PP (Figure 5a). With rapid revegetation and high growth rates, however, annual water use by PP begins to exceed the constant water use of the LBA stands within 8-10 years. In general, initially high water yields from PP stands were balanced or offset by greater water use as stands mature (Figure 5b), suggesting that stands managed for LBA can have similar or substantially greater CWY than PP stands depending on three factors: (1) the magnitude of reduction in basal area (e.g., LBA-14 *vs.* LBA-8); (2) assumptions about early PP stand water yield (e.g., PP-Low *vs.* PP-High); and (3) the use of fire as a management tool to reduce understory vegetation (e.g., LBA-14 *vs.* LBA-14 + Fire).

Table 2 presents the mean and standard deviation of CWY estimates for each management scenario calculated over 1,000 model simulations with varying parameter inputs, demonstrating how uncertainty in the regression equations that underlie the model affect uncertainty in CWY calculations. Model realizations with the highest estimates of water yield were associated with stochastic parameter selection that yielded low estimates of both LAI and ET/PPT, whereas low water yield estimates were associated with parameters that yielded high values of LAI and ET/PPT. Uncertainty was smaller for both PP scenarios (average SD = 1,270 mm) than it was for all LBA scenarios (average SD = 1,720 mm) due to better-constrained estimates of LAI in PP after year 14 (i.e., 95% CI = 0.49; Figure 4) compared with the LBA scenarios (95% CI = 0.99; Figure 3).

Differences in CWY between PP and LBA scenarios (ΔCWY) are summarized in Figure 6. These results suggest an increase in CWY from converting PP stands to LBA management, with two major sources of uncertainty: (1) uncertainty in the estimated water use of young PP (i.e., the differences in ΔCWY of LBA scenarios when comparing with PP-High *vs.* PP-Low); and (2) uncertainty in the regression equations (i.e., standard deviations of ΔCWY of each scenario calculated over 1,000 model realizations). Maximum values of ΔCWY for each scenario were realized when stochastic parameter selection yielded high estimates of LAI in PP (based on stand age) and low estimates of LAI in LBA (based on basal area); the opposite parameterization yielded minimum values of ΔCWY, leading to relatively large ranges in predicted ΔCWY when parameters were selected at opposite ends of the input parameter distributions. With these ranges noted, mean modeled ΔCWYs were positive for all LBA scenarios, with the exception of LBA-14 when compared with PP-High; adding recurrent fire to LBA-14, however, resulted in positive mean ΔCWY under both PP assumptions. These results demonstrate the potential for large increases in CWY, particularly for landscapes managed at the lowest basal areas (i.e., ΔCWY of between 41 and 64% for the LBA-8 scenario; Figure 6).

TABLE 2. Simulated Mean and Standard Deviation (shown in parentheses) of 25-Year Cumulative Water Yield (CWY) from Planted Pine (PP) Plantation, Managed Systems Maintained at Low Basal Areas of 8, 10, 12, and 14 m^2/ha (LBA-8, LBA-10, LBA-12, and LBA-14), and LBA Management with the Addition of Recurrent Fire to Clear Understory Vegetation (LBA-14+Fire).

Scenario	CWY (mm)
PP-High	5,140 (1,320)
PP-Low	4,440 (1,220)
LBA-8	7,260 (1,740)
LBA-10	6,240 (1,740)
LBA-12	5,420 (1,740)
LBA-14	4,750 (1,740)
LBA-14+Fire	6,150 (1,640)

Note: PP-High and PP-Low represent high and low estimates of PP water yield based on assumptions about leaf area index and water use of young PP.

Water Yield Potential from Management at Local and Regional Scales

At the Hargrove Pasture site, mean basal area was 19.2 ± 9.4 m^2/ha across individual stands ranging in area between 0.1 and 69 ha. These areas were used to scale-up area-based water yields (in mm) to total volumetric water yield from the 1,700-ha site. Predicted current annual water yield from these stands (average ± SD of 1,000 model realizations) was $2.67 \pm 1.15 \times 10^6$ m^3/yr (1.93 ± 0.83 million gallons per day [mgd]). Reducing current basal areas to a constant value increased annual water yield by $0.56 \pm 0.05 \times 10^6$ m^3/yr (0.40 ± 0.04 mgd) and $2.28 \pm 0.05 \times 10^6$ m^3/yr (1.65 ± 0.04 mgd) for the LBA-14 and LBA-8 scenarios, respectively (an increase of 21-86% for mean values). Adding a three-year fire rotation to remove understory vegetation by assuming average understory LAI reduction of 50% (i.e., the average of cycling through 100, 50, and 0% understory LAI removal over a three-year fire cycle) augmented the effect of the LBA-14 scenario, with the estimated increase in water yields vis-à-vis existing management of $1.49 \pm 0.09 \times 10^6$ m^3/yr (1.08 ± 0.06 mgd), or 56%. Uncertainty in modeled

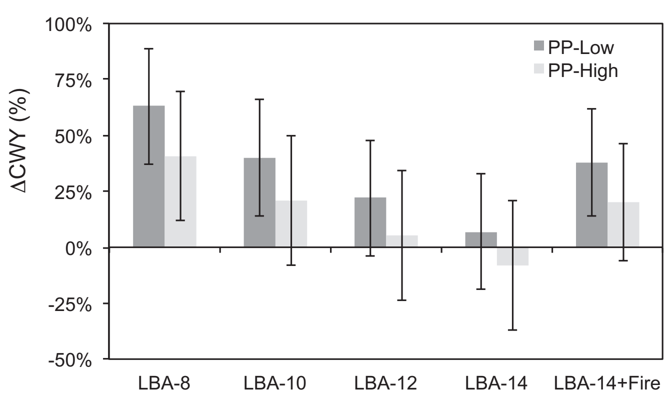

FIGURE 6. Change in Cumulative Water (ΔCWY) from Converting Planted Pine (PP) Stands to Different Low Basal Area (LBA) Management Scenarios Shown as Modeled Mean and Standard Deviation over 1,000 Model Realizations. PP-High and PP-Low represent high and low estimates of PP water yield based on assumptions about leaf area index and water use of young PP.

ΔCWY in this analysis was lower (i.e., compared to uncertainty in ΔCWY between PP and LBA stands presented above) because both current and LBA water yield at the Hargrove site were calculated using the basal area-to-LAI regression in Figure 3, whereas LAI for PP and LBA stands was calculated with independent relationships. Thus, stochastically generated regression parameters relating basal area to LAI and LAI to ET/PPT at the Hargrove site were the same for each scenario within model realizations.

Table 3 summarizes mean modeled ΔCWY (reported in mgd for comparison to regional consumptive use) that might be realized through conversion of PP plantation to different LBA scenarios at the regional scale for a number of different areal footprints, including: (1) all publicly and privately owned PP within the SJRWMD (327,667 ha); (2) all publicly owned and managed PP (local, state, and federal) within the SJRWMD boundary (65,413 ha); and (3) all publicly and privately owned PP in Flagler County (location of the Hargrove Pasture) (24,978 ha) (Figure 1). The ranges of simulated ΔCWY in Table 3 represent the *mean* modeled increase in stand water yields calculated using high and low estimates of young stand water yield in PP (i.e., using PP-High and PP-Low in Figure 4). These results suggest that large increases in water yield (up to 53 mgd) are possible from the conversion of PP to LBA-8 on existing publicly owned and managed lands in the SJRWMD. Even larger subsidies may be realized under lower LBA scenarios with fire (e.g., LBA-8 + Fire); however, further empirical data are required to reasonably establish the magnitude of this effect. Large-scale conversion of all PP to LBA management at the watershed scale, although likely not feasible, would produce an even larger potential water yield impact (i.e., from 202 to 268 mgd of additional water yield under the LBA-8 scenario). On the other hand, net benefits from conversion of PP into LBA-12 or LBA-14 are small and uncertain, particularly when assuming high water yield from young PP stands (PP-High). Although these increases were calculated using the best estimate (i.e., the mean) of modeled water yield, uncertainty around ΔCWY predictions for each scenario (see above) demonstrates the potential for an even greater range in possible water yield changes resulting from revised land management.

TABLE 3. Mean Predicted Increase (or decrease, if negative) in Cumulative Water (ΔCWY) from Converting Planted Pine (PP) Stands to Different Low Basal Area (LBA) Management Scenarios Scaled Up over Different Areal Footprints, Presented as Volumetric Daily Water Yield (in millions of gallons per day, mgd).

	ΔCWY (mgd)		
Scenario	**All PP in SJRWMD**	**Public PP in SJRWMD**	**PP in Flagler City**
LBA-8	202-268	40-53	15-20
LBA-10	104-170	21-34	8-13
LBA-12	27-92	5-18	2-7
LBA-14	−37-29	−7-6	−3-2
LBA-14+Fire	96-162	19-32	7-12

Note: ΔCWY ranges in each scenario represent mean modeled increases (or decreases) calculated with PP-Low and PP-High.

DISCUSSION

The relationship between forest cover and water yield has been well documented, but previously published studies lack the ability to predict water yield on a unit area basis as a function of stand structure. Predicting water yield as function of stand structure and management requires an understanding of evapotranspiration rates relative to rainfall (ET/PPT) across a range of management scenarios. In this study, published ET and stand structure data were used to relate ecosystem water use to forest structure and to build a model to estimate changes in cumulative water yield (ΔCWY) due to changes in management from high-intensity planted pine (PP) to more natural, low basal area (LBA) systems.

Applying this model at the stand scale allowed us to estimate that conversion from PP to LBA management for an existing 1,700-ha PP stand has the potential to increase water yield by 21-86% compared with current conditions, and could provide between 0.40 and 1.65 mgd of *additional* water yield to the regional hydrologic system. With the ratio of water demand relative to supply predicted to increase in the southeastern U.S. (e.g., Sun *et al.*, 2008), large private landowners (such as timber companies) may be an important partner in developing alternative water "sources," and could be encouraged to convert land from high-water-use to low-water-use ecosystems through economic incentives (e.g., "hydrologic easements") that help subsidize management strategies to maintain low basal area including thinning, shelterwood harvesting, and understory management. These types of easements may be particularly appealing to timber producers as a way to: (1) buffer market volatility by providing a consistent source of income from a portion of their land, and (2) mitigate the cost of taking marginal lands (overly wet or dry, poor soils, etc.) out of production. Payments for increased water yield align well with other public priorities (e.g., biodiversity and water quality), for which economic incentives already exist (Mayrand and Paquin, 2004), and this process may be a way for local, state, and federal agencies (including public utilities) to expand the footprint of conservation lands without the acquisition, maintenance, and management costs associated with land purchase. Payments for increases in water yield could greatly expand the area of southeastern pinelands managed in a more historical state. Importantly, however, a transparent and low-cost process for monitoring compliance would be critical to the success of this type of program.

At the regional scale, the magnitude of potential water yield subsidies from upland conversion is large but uncertain. For example, converting PP in publicly owned and managed parcels in the SJRWMD into the LBA-8 scenario has the potential to increase regional water yield by 40-53 mgd (Table 3). Given current public land management goals (maintaining widely spaced trees and a diverse understory using selective thinning and prescribed fire), conversion of the majority of these lands to LBA management is viable, and the hydrologic benefit of their conversion may motivate additional funding for their continued maintenance in this condition. Moreover, our model simulations were for slash pine stands (in both LBA and PP stands), whereas a common goal for public lands is reintroduction of longleaf pine (Dey *et al.*, 2004), which has lower water use rates (Gonzalez-Benecke *et al.*, 2011), highlighting the potential hydrologic implications of longleaf pine restoration.

At the largest scale, changing management of all public and private PP in SJRWMD to LBA-8 has the potential to increase regional water yield by 202-268 mgd (Table 3), equivalent to 17-22% of the total freshwater withdrawals in the SJRWMD (1,207 mgd of surface water and groundwater in 2005) (SJRWMD, 2012). However, the conversion of all PP to the lowest LBA scenarios is unlikely (forestry provides US$8.8 billion in annual revenue in Florida alone [Hodges *et al.*, 2005]). A more feasible approach would be to prioritize management for LBA+Fire on public lands while developing mechanisms to compensate private landowners for reducing basal areas and implementing understory management on productive lands, as well as for taking marginal lands out of production.

At all scales, it is important to note the uncertainty around predicted water yield increases, including possible decreases in water yield, particularly for conversion from PP to the LBA-14 scenario (Figure 6 and Table 3). This uncertainty critically highlights the importance of future research to pursue site-specific monitoring of water use, particularly in young PP stands, to verify the benefits that accrue from altered management. We presented two estimates of mean PP water yield to account for the uncertainty in total LAI (canopy and understory), and thus water use, of young PP stands. Sampson *et al.* (2011) also recognized the uncertainty of water use by understory species in young stands and highlighted the underestimation of ET in hydrologic models that results when understory LAI is not included. Moreover, this analysis suggests that water use by PP plantation is in the same range as that in LBA stands managed at the high end of the LBA scenarios (i.e., stands managed at 14 m^2/ha), emphasizing the relative water efficiency of pine plantation, particularly in comparison with irrigated agriculture, which accounts for 40% of all freshwater withdrawals in Florida (Marella, 2009).

In addition to addressing the uncertainty of water use by young PP, we also determined the uncertainty in the regressions that underlie our water yield model and quantified how that uncertainty propagated into predictions of ΔCWY between management scenarios. The standard deviations of ΔCWYs over 1,000 model realizations (Figure 6), which were similar in magnitude across scenarios (122 ± 70 mm), highlight the large range in potential ΔCWY from converting PP to LBA management and illustrates the need to reduce model input uncertainty to better constrain the magnitude (and in some cases sign) of ΔCWY. For example, when considering the PP-Low scenario, conversion to LBA management most likely produces a net water yield benefit for the LBA-8, LBA-10, and LBA-14 + Fire scenarios, but uncertainty around the mean makes the benefits of LBA-12 and LBA-14 less clear (Figure 6). Given the independent parameterization of the regression equations relating stand age to LAI (for PP) and basal area to LAI (for LBA), these estimates of uncertainty are likely conservative. This is supported by the much smaller uncertainty range around predicted values of ΔCWY at the Hargroves Pasture site, where only the basal area-to-LAI relationship was applied.

Both climate and stand structure (especially LAI; Vose *et al.*, 1994) are primary determinants of ecosystem water use (Edwards and Troendle, 2012). Our model limited ET predictor variables to stand attributes, namely LAI as the predictor of ET/PPT, to isolate the effects of stand management on water use, adding uncertainty to modeled water yields (Figure 2; Table 2). Although our intent was to isolate management — not climate — effects, we restricted the analysis to studies performed in Florida to partially control for climatic variability. Within these studies, we found that LAI explained 53% of the variation in ET/PPT ratios. It is likely that the majority of the unexplained variability is due to temporal and spatial climatic variability. For example, Sun *et al.* (2011) predicted monthly ecosystem ET across a range of biomes using potential ET (PET), rain, and LAI, which together explained 85% of the variability in ET; notably LAI was the strongest predictor, supporting our inferences of the water use effects from more subtle differences in LAI within a specific ecosystem type.

While our limited dataset and simplified modeling approach introduced uncertainty in the magnitude of ΔCWY from conversion of PP to LBA, previous observational and modeling studies offer some support for our results. Paired watershed studies in the coastal plain of North Carolina and South Carolina have measured water table rise (Williams and Lipscomb, 1981; Grace *et al.*, 2006; Amatya and Skaggs, 2008) and increased surface outflow by 15% (Amatya and Skaggs, 2008) and 100% (Grace *et al.*, 2006) following thinning. Using a site-specific parameterized model, Tian *et al.* (2012) simulated reductions in LAI and ET that resulted from thinning a North Carolina loblolly PP, with commensurate increases in drainage outflow (ca. 10% increase). For the same loblolly PP, McCarthy and Skaggs (1992) simulated drainage outflow increases of 74% for the year after thinning and ca. 13% over a 25-year rotation when comparing stands with two thinnings *vs.* unthinned conditions, highlighting the potential for net water yield increases with more frequent and perhaps intensive thinning. Similar to clear-cut effects, thinning effects can be transient, with hydrologic recovery to preharvest water yields in as little as three years (Amatya and Skaggs, 2008). Thinning, however, can be implemented frequently (seven-year cycle recommended for shelterwood management methods; Dey *et al.*, 2004) to maintain a LBA system and sustain increased water yield.

Compared with harvest effects, studies investigating water yield effects of prescribed fire, a commonly used tool for understory management on PPs and for improved habitat on public lands, are extremely limited and provide mixed results (e.g., Amatya *et al.*, 2006a), indicating an important knowledge gap (Edwards and Troendle, 2012). Our modeled water yield subsidies from LBA management were amplified by the addition of prescribed fires. For example, the water yield benefit realized from converting PP to LBA-14 without fire is uncertain (i.e., the estimated mean change in water yield is between −7.6 and 6.8% for the PP-High and PP-Low scenarios, respectively); however, simulating a three-year understory fire return interval (LBA-14+Fire) increases mean modeled water yield by 20-39% over PP (Figure 6). We note that the estimates of additional water yield due to recurrent fire are poorly constrained due to a paucity of data, and for this reason do not present the results of adding fire to the lower LBA scenarios in Figure 6 or in the analysis of regional water yield in Table 3. However, applying the same metrics and methodology used for developing the LBA-14 + Fire scenario to produce a LBA-8 + Fire scenario (i.e., reducing total LAI by 23, 11.5, and 0% in a three-year fire cycle) would increase mean modeled water yield by 63-88% over PP. If applied to all publicly owned and managed lands in the SJRWMD, this scenario would yield an additional 61-74 mgd over PP (compared with an additional yield of 40-53 mgd for the LBA-8 scenario without fire; Table 3). Although the magnitude of these water yield subsidies is promising, they are tentative, and further research to quantify the allocation of LAI and ET between the understory and canopy is needed to accurately quantify the hydrologic benefits of fire.

In contrast to more site-specific and highly parameterized models (e.g., McCarthy and Skaggs, 1992; Tian *et al.*, 2012), we limited predictor variables to stand attributes to predict variation in water yield independent of other site-specific characteristics such as soil type, topography, drainage features, and interannual climatic variability. Although such simplification reduces the ability of our model to accurately predict ET/PPT for a specific stand, it greatly increases model generality and our ability to demonstrate the potential for changes in water yield resulting from different management approaches. However, we strongly emphasize that accurately parameterizing a predictive model for widespread use as policy and planning tool requires additional studies of ET fluxes and how they are affected by stand attributes, climate, physiographic conditions, and management alternatives. Further research is also required to track the ultimate fate of the additional water yield (i.e., local/regional surface water bodies, surficial/intermediate/deep aquifers, etc.) to more explicitly quantify the hydrologic benefits of LBA management to downstream surface water and groundwater resources.

Forest lands in the southeastern U.S. remain a crucial nexus in the hydrologic cycle, affecting the quantity, quality, and timing of water to both surface and groundwater bodies. They are also a vital component of the regional economy. Identifying land management strategies that reduce ecosystem water use intensity will be vital to maintaining the sustainability of forest and water resources and protecting natural ecosystems as populations continue to increase and water resources are further depleted and degraded. With over 16 million acres of forested land in Florida (Brown, 2005), forest restoration and management (already a goal of many land management agencies) may be a key element of this water conservation strategy. Although the hydrologic implications of land management to maintain constant low basal areas and frequent prescribed fires are promising, further research is required to better quantify: (1) fire effects, particularly in systems managed at basal areas that mimic "historic" ecosystems (e.g., 8-10 m^2/ha); (2) water use in young (<6-year-old) PP plantations; and (3) the ultimate destination of the additional water yielded from LBA-managed ecosystems.

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LITERATURE CITED

Abrahamson, W.G. and D.C. Hartnett, 1990. Pine Flatwoods and Dry Prairies. *In*: Ecosystems of Florida, R.L. Myers and J.J. Ewel (Editors). University of Central Florida Press, Orlando, Florida, pp. 103-149.

Amatya, D.M., M. Miwa, C.A. Harrison, C.C. Trettin, and G. Sun, 2006a. Hydrology and Water Quality of Two First Order Forested Watersheds in Coastal South Carolina. American Society of Agriculture and Biological Engineers Paper 062182.

Amatya, D.M. and R.W. Skaggs, 2008. Effects of Thinning on Hydrology and Water Quality of a Drained Pine Forest in Coastal North Carolina. American Society of Agriculture and Biological Engineers Paper 701P0208cd.

Amatya, D.M., R.W. Skaggs, C.D. Blanton, and J.W. Gilliam, 2006b. Hydrologic and Water Quality Effects of Harvesting and Regeneration of a Drained Pine Forest. *In*: Hydrology and Management of Forested Wetlands: Proceedings of the International Conference, St. Joseph, Missouri, Williams and Thomas (Editors). American Society of Agriculture and Biological Engineers, pp. 538-551.

Amatya, D.M., R.W. Skaggs, and J.D. Gregory, 1996. Effects of Controlled Drainage on the Hydrology of Drained Pine Plantations in the North Carolina Coastal Plain. Journal of Hydrology 181:211-232.

Anderson, H.W., M.D. Hoover, and K.G. Reinhart, 1976. Forests and Water: Effect of Forest Management on Floods, Sedimentation, and Water Supply. USDA Forest Service General Technical Report PSW-18, Berkeley, California.

Batelaan, O., F. De Smedt, and L. Triest, 2003. Regional Groundwater Discharge: Phreatophyte Mapping, Groundwater Modelling and Impact Analysis of Land-use Change. Journal of Hydrology 275:86-108.

Bidlake, W.R., W.M. Woodham, and M.A. Lopez, 1996. Evapotranspiration from Areas of Native Vegetation in West-Central Florida. USGS Water-Supply Paper 2430.

Bliss, C.M. and N.B. Comerford, 2002. Forest Harvesting Influence on Water Table Dynamics in a Florida Flatwoods Landscape. Soil Science Society American Journal 66:1344-1349.

Bosch, J.M. and J.D. Hewlett, 1982. A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration. Journal of Hydrology 55:3-23.

Bracho, R., T.L. Powell, S. Dore, J. Li, and C.R. Hinkle, 2008. Environmental and Biological Controls on Water and Energy Exchange in Florida Scrub Oak and Pine Flatwoods Ecosystems. Journal of Geophysical Research 113:G02004, doi: 10.1029/2007JG000469.

Brown, M.J., 2005. Florida's Forests-2005 Update. USDA Forest Service Resource Bulletin: SRS-118.

Carter, M.C. and C.D. Foster, 2004. Prescribed Burning and Productivity in Southern Pine Forest: A Review. Forest Ecology and Management 191:93-109.

Coates, K. and G. Lewis, 2010. Tate's Hell State Forest Hydrologic Restoration Plan, Volume II. Northwest Florida Water Management District, Havana, FL and Florida Division of Forestry, Carrabelle, Florida, pp. 1-44.

Dey, D.C., J.C. Brissette, C.J. Schweitzer, and J.M. Guldin, 2004. Silviculture of Forests in the Eastern United States. *In*: Cumulative Watershed Effects of Fuel Management in the Eastern United States, R. Lafayette, M. Brooks, J. Potyondy, L. Audin, S. Krieger, and C. Trettin (Editors). Department of Agriculture Forest Service, Southern Research Station, Asheville, North Carolina. General Technical Report SRS-161, pp. 7-40.

Dube, S., A.P. Plamondon, and R.L. Rothwell, 1995. Watering Up After Clear-Cutting on Forested Wetlands of the St. Lawrence Lowland. Water Resources Research 31:1741-1750.

Edwards, P.J and C.A. Troendle, 2012. Water Yield and Hydrology. *In*: Cumulative Watershed Effects of Fuel Management in the Eastern United States, R. Lafayette, M. Brooks, J. Potyondy, L. Audin, S. Krieger, and C. Trettin (Editors). Department of Agriculture Forest Service, Southern Research Station, Asheville, North Carolina. General Technical Report SRS-161, pp. 229-281.

Ewel, K.C. and H.L. Gholz, 1991. A Simulation Model of the Role of Belowground Dynamics in a Florida Pine Plantation. Forest Science 37:397-438.

Freeman, J.E. and S. Jose, 2009. The Role of Herbicide in Savanna Restoration: Effects of Shrub Reduction on the Understory and Overstory of a Longleaf Pine Flatwoods. Forest Ecology and Management 257:978-986.

Gholz, H.L. and K.L. Clark, 2002. Energy Exchange Across a Chronosequence of Slash Pine Forests in Florida. Agricultural and Forest Meteorology 112:87-102.

Gholz, H.L. and R.F. Fisher, 1982. Organic Matter Production and Distribution in Slash Pine (*Pinus Elliotti*) Plantations. Ecology 63:1827-1839.

Gholz, H.L., S.A. Vogel, W.P. Cropper, Jr., K. McKelvey, K.C. Ewel, R.O. Teskey, and P.J. Curran, 1991. Dynamics of Canopy Structure and Light Interception in *Pinus Elliotti* Stands, North Florida. Ecological Monographs 61:33-51.

Gonzalez-Benecke, C.A., T.A. Martin, and W.P. Cropper, Jr., 2011. Whole-Tree Water Relations of Co-Occurring Mature *Pinus Palustris* and *Pinus Elliottii* var. *Elliotti*. Canadian Journal of Forest Research 41:509-523.

Gower, S.T., C.J. Kucharik, and J.M. Norman, 1999. Direct and Indirect Estimation of Leaf Area Index, F_{APAR}, and Net Primary Production of Terrestrial Ecosystems. Remote Sensing of Environment 70: 29-51.

Grace, J.M., R.W. Skaggs, and G.M. Chescheir, 2006. Hydrologic and Water Quality Effects of Thinning Loblolly Pine. Transactions of the Agriculture and Biological Engineers 49:645-654.

Granier, A., V. Boby, J.H. Gash, J. Gelpe, B. Saugier, and W.J. Shuttleworth, 1990. Vapour Flux Density and Transpiration Rate Comparisons in a Stand of Maritime Pine (*Pinus Pinaster* Ait.) in Les Landes Forest. Agricultural and Forest Meteorology 51:309-319.

Hanson, R.L, 1991. Evapotranspiration and Droughts. *In*: National Water Summary 1988-89—Hydrologic Events and Floods and Droughts, R.W. Paulson, E.B. Chase, R.S. Roberts, and D.W. Moody (Editors). USGS Water-Supply Paper 2375, pp. 99-104.

Harbaugh, A.W., 2005. MODFLOW-2005. U.S. Geological Survey Modular Ground-Water Model—The Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Helvey, J.D., 1980. Effects of a North Central Washington Wildfire on Runoff and Sediment Production. Journal of the America Water Resources Association 16:627-634.

Hodges, A.W., W.D. Mulkey, J.R. Alavalapati, D.R. Carter, and C.F. Kiker, 2005. Economic Impacts of the Forest Industry in Florida, 2003. Final Report to the Florida Forestry Association, Tallahassee, Florida.

Hornbeck, J.W., M.B. Adams, E.S. Corbett, E.S. Verry, and J.A. Lynch, 1993. Long-Term Impacts of Forests Treatments on

Water Yield: A Summary for Northeastern USA. Journal of Hydrology 150:323-344.

Jackson, C.R., G. Sun, D. Amatya, W.T. Swank, M. Riedel, J. Patric, T. Williams, J.M. Vose, C. Trettin, W.M. Aust, R.S. Beasley, H. Williston, and G.G. Ice, 2004. Fifty Years of Forest Hydrology in the Southeast. *In*: A Century of Forest and Wildland Watershed Lessons, G.G. Ice and J.D. Stednick (Editors). The Society of American Foresters, Bethesda, Maryland, pp. 33-112.

Karl, T.R., J. M. Melillo, and T.C. Peterson, 2009. Global Climate Change Impacts in the United States. Cambridge University Press, New York, New York.

Knowles L., Jr., 1996. Estimation of Evapotranspiration in the Rainbow Springs and Silver Springs Basins in North-Central Florida. USGS Water-Resources Investigations Report 96-4024.

Legendre, P. and L. Legendre, 1998. Numerical Ecology: Developments in Environmental Modeling 20, 2nd Edition. Elsevier, Amsterdam, The Netherlands.

Liu, S., 1996. Evapotranspiration From Cypress (*Taxodium Ascendens*) Wetlands and Slash Pine (*Pinus Elliottii*) Uplands in North-Central Florida. Ph.D. Dissertation, University of Florida, Gainesville, Florida.

Liu, S., H. Riekerk, and H.L. Gholz, 1998. Simulation of Evapotranspiration From Florida Pine Flatwoods. Ecological Modeling 114:19-34.

Lu, J., G. Sun, S.G. McNulty, and N.B. Comerford, 2009. Sensitivity of Pine Flatwoods Hydrology to Climate Change and Forest Management in Florida, USA. Wetlands 29:826-836.

Mallet, B., 2009. Timber Management Recommendations, T. Mabry Carlton Memorial Reserve, Sarasota County Environmentally Sensitive Lands Program. Florida Division of Forestry, pp. 1-7.

Marella, R.L., 2009. Water Withdrawals, Use, and Trends in Florida, 2005. U.S. Geological Survey Scientific Investigations Report 2009-5125.

Mayrand, K. and M. Paquin, 2004. Payments for Environmental Services: A Survey and Assessment of Current Schemes. Unisféra International Centre. The Commission for Environmental Cooperation of North America Report. Montreal, Canada.

McCarthy, E.J. and R.W. Skaggs, 1992. Simulation and Evaluation of Water Management Systems for a Pine Plantation Watershed. Southern Journal of Applied Forestry 16:44-52.

NOAA, 2012. National Weather Service River Forecast Center. Southeast Flood Climatology Resources. http://www.srh.noaa.gov/serf/?n=climohydro, *accessed* October 3, 2012.

Oren, R., B.E. Ewers, P. Todd, N. Phillips, and G. Katul, 1998. Water Balance Delineates the Soil Layer in Which Moisture Affects Canopy Conductance. Ecological Applications 84:990-1002.

Outcalt, K.W. and D.G. Brockway, 2010. Structure and Composition Changes Following Restoration Treatments of Longleaf Forests on the Gulf Coastal Plain of Alabama. Forest Ecology and Management 259:1615-1623.

Phillips, N. and R. Oren, 2001. Intra- and Inter-Annual Variation in Transpiration of a Pine Forest. Ecological Applications 11:385-396.

Powell, T.L., G. Starr, K.L. Clark, T.A. Martin, and H.L. Gholz, 2005. Ecosystem and Understory Water and Energy Exchange for a Mature, Naturally Regenerated Pine Flatwoods Forest in North Florida. Canadian Journal of Forest Research 35:1568-1580.

Riekerk, H., 1985. Lysimetric Evaluation of Pine Forest Evapotranspiration. *In*: The Forest-Atmosphere Interaction, B.A. Hutchinson and B.B. Hicks (Editors). D. Reidel, Dordrecht, The Netherlands, pp. 193-308.

Riekerk, H., 1989. Influence of Silviculture Practices on the Hydrology of Pine Flatwoods in Florida. Water Resources Research 25:713-719.

Roberts, J., 1983. Forest Transpiration: A Conservative Hydrological Process? Journal of Hydrology 66:133-141.

Sampson, D.A., D.M. Amatya, C.D. Blanton Lawson, and R.W. Skaggs, 2011. Leaf Area Index (LAI) of Loblolly Pine and Emergent Vegetation Following a Harvest. Transactions of the American Society of Agricultural and Biological Engineers 54:2057-2066.

Scott, D.F., 1993. The Hydrological Effects of Fire in South African Mountain Catchments. Journal of Hydrology 150:409-432.

SJRWMD, 2012. Total Water Use for 1995, 2005, and Total Water Demand for 2030, by Category of Use, in the St. Johns River Water Management District. http://www.sjrwmd.com/pdfs/Total_Water_Use-Demand_By_Category.pdf, *accessed* October 3, 2012.

Sumner, D.M., 2001. Evapotranspiration From a Cypress and Pine Forest Subjected to Natural Fires, Volusia County, Florida, 1998-99. USGS Water-Resources Investigations Report 01-4245.

Sun, G., K. Alstad, J. Chen, S. Chen, C.R. Ford, G. Lin, C. Liu, N. Lu, S.G. McNulty, H. Miao, A. Noormets, J.M. Vose, B. Wilske, M. Zeppel, Y. Zhang, and Z. Zhang, 2011. A General Predictive Model for Estimating Monthly Ecosystem Evapotranspiration. Ecohydrology 4:245-255.

Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen, 2008. Impacts of Multiple Stresses on Water Demand and Supply Across the Southeastern United States. Journal of the American Water Resources Association 44:1441-1457.

Sun, G., S.G. McNulty, J.P. Shepard, D.M. Amatya, H. Riekerk, N.B. Comerford, W. Skaggs, and L. Swift, Jr., 2001. Effects of Timber Management on the Hydrology of Wetland Forests in the Southern United States. Forest Ecology and Management 143:227-236.

Sun, G., A. Noormets, M.J. Gavazzi, S.G. McNulty, J. Chen, J.C. Domec, J.S. King, D.M. Amatya, and R.W. Skaggs, 2010. Energy and Water Balance of Two Contrasting Loblolly Pine Plantations on the Lower Coastal Plain of North Carolina, USA. Forest Ecology and Management 259:1299-1310.

Sun, G., H. Riekerk, and N.B. Comerford, 1998. Modeling the Hydrologic Impacts of Forest Harvesting on Florida Flatwoods. Journal of the American Water Resources Association 34:843-854.

Tian, S., M.A. Youssef, R.W. Skaggs, D.M. Amatya, and G.M. Chescheir, 2012. Modeling Water, Carbon, and Nitrogen Dynamics of Two Drained Pine Plantations Under Intensive Management Practices. Forest Ecology and Management 264:20-36.

Vose, J.M. and H.L. Allen, 1988. Leaf Area, Stemwood Growth, and Nutrition Relationships in Loblolly Pine. Forest Science 34:547-563.

Vose, J.M., P.M. Dougherty, J.N. Long, F.W. Smith, H.L. Gholz, and P.J. Curran, 1994. Factors Influencing the Amount and Distribution of Leaf Area of Pines Stands. Ecological Bulletins (Copenhagen) 43:102-114.

Williams, T.M. and D.J. Lipscomb, 1981. Water Table Rise After Cutting on Coastal Plain Soils. Southern Journal of Applied Forestry 5:46-48.

Xu, Y., J.A. Burger, W.M. Aust, S.C. Patterson, M. Miwa, and D.P. Preston, 2002. Changes in Surface Water Table Depth and Soil Physical Properties After Harvest and Establishment of Loblolly Pine (*Pinus Taeda* L.) in Atlantic Coast Plain Wetlands of South Carolina. Soil and Tillage Research 63:109-121.