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Potential Implications for Expansion of Freeze-Tolerant *Eucalyptus* Plantations on Water Resources in the Southern United States

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The potential expansion of freeze-tolerant (FT) *Eucalyptus* plantations in the United States has raised concerns about the implications for water resources. Modeling was used to examine the potential effects of expanding the distribution of FT *Eucalyptus* plantations in US Department of Agriculture Plant Hardiness Zones 8b and greater on water yield (*Q*). Analyses focused on two scales: the stand scale and the regional scale at the 12-digit Hydrologic Unit Code (HUC) watershed. Results suggested that the stand-level implications of planting FT *Eucalyptus* on *Q* could vary by location, the land cover type before *Eucalyptus* establishment, and the hydrologic conditions of the planting site and surrounding area. Compared with that for some pine plantations, *Q* at the stand level could be equal to or reduced by as much as to 130 mm year^{-1} (a reduction of 9–16% of precipitation) near the end of the rotation or on sites when leaf area index (LAI) is 4 m^2 m^{-2} and reduced by as much as 500 mm year^{-1} (a reduction of 33–63% of precipitation) when LAI is 5 m^2 m^{-2}. In contrast, at the scale of conversion indicated by an economic analysis as most likely (e.g., $<$20% conversion of conifer to FT eucalyptus), reductions on *Q* at the 12-digit HUC scale will be negligible.

Keywords: evapotranspiration, streamflow, modeling, water budget

Forest plantations supply an increasing share of fiber throughout the world, with their area expanding at a rate of 5 million ha year^{-1} between 2000 and 2010 (Food and Agriculture Organization of the United Nations 2012). In the Southeastern United States, the 16 million ha of planted forests are almost exclusively pines (*Pinus* spp.) and are an important source of softwood forest products. Hardwood forest products in the region are mostly sourced from natural stands and have become increasingly scarce as indicated by rising real prices (Wear et al. 2007). *Eucalyptus,* a highly productive genus native to Australia and Indonesia, has been planted across large areas of Asia, Africa, and South America, but its application in the United States has been limited by environmental factors, especially sensitivity to freezing temperatures of the faster growing species. The development of more freeze-tolerant (FT) *Eucalyptus* (a hybrid, *Eucalyptus grandis* × *Eucalyptus urophylla*), through genetic modification or breeding, has the potential to greatly expand the range of *Eucalyptus.* Genetically modified *Eucalyptus* can now tolerate environmental conditions in US Department of Agriculture (USDA) Plant Hardiness Zones 8b (annual minimum temperature >9.4° C) and greater (Hinchee et al. 2011). This range expansion offers the potential to greatly increase hardwood fiber production in many areas of the United States. For example, rates of potential productivity for *Eucalyptus* range from 18 to 67 green Mg ha^{-1} year^{-1} (Stanturf et al. 2013, Wear et al. 2014), and this new material could support industries currently using hardwood forest products as an input and may make novel industrial applications economically viable.

The potential expansion of FT *Eucalyptus* plantations in the United States has raised questions about a variety of environmental and biological issues including fire risk, biodiversity, and water resources (Stanturf et al. 2013). Concerns about the effects of *Eucalyptus* plantations on water resources are based on numerous studies of evapotranspiration (ET = transpiration + interception evaporation) and stand water balance from across the world (e.g., Farley et al. 2005, Ferraz et al. 2013, King et al. 2013). *Eucalyptus* has one of the highest ET rates among many tree species (Whitehead and Beadle 2004, Farley et al. 2005, King et al. 2013), driven by high stomatal conductance, evergreen leaf habit, physiological characteristics that

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increase drought tolerance, and rooting characteristics that can exploit deep soil water reserves (White et al. 2002). *Eucalyptus* also has a high water use efficiency (WUE = kg biomass produced/kg water transpired) (Stape et al. 2004), even in the fastest growing stands (Binkley 2012). High WUE could offset some of the potential negative impacts of high ET on water resources (King et al. 2013); however, this offset would only be realized if less land area was planted in species with a lower WUE. Regardless of higher WUE, substantial reductions or elimination of streamflow and/or groundwater recharge from increased absolute water use could have detrimental impacts on water resources and associated aquatic ecosystems, especially at local scales. To our knowledge, this study represents the first critical analysis of the potential impacts of *Eucalyptus* on water resources in the southern United States.

Three factors require consideration in the evaluation of the potential effects of FT *Eucalyptus* on ET or water resources. First, the context for interpreting changes in ET and water yield (Q) from planting *Eucalyptus* will vary based on what land cover serves as a reference. For example, among alternative forest covers, ET varies considerably across the southern United States, ranging from 480 mm year^{-1} in hardwoods (Stoy et al. 2006) to ~1,200 mm year^{-1} in slash, loblolly, and white pine plantations (Ford et al. 2007, Sun et al. 2010; Table 2). Different interpretations are likely when *Eucalyptus* ET is compared with a high versus a low ET land cover type reference. Second, the relative effect on Q depends in large part on the balance between precipitation (P) and ET. Assuming that ET is comparable among areas of high and low precipitation, the *relative impacts* (i.e., as a percentage of flow under reference conditions) of higher ET on Q are lower in areas where precipitation is higher. Third, the interpretation is probably scale and location dependent. For example, small (e.g., <20 ha), infrequent, and well-dispersed plantations over a large land area would likely limit impacts to the local scale, such as first-order streams draining the *Eucalyptus* stand, whereas impacts at larger spatial scales would probably be minor and undetectable.

Predicting the configuration of plantations to support end uses (e.g., fiber or bioenergy) is challenging; however, economic factors such as mill locations, demand, and transportation costs will influence the size and spatial distribution of plantations. That is, we would expect a greater concentration of plantations in areas where financial returns are likely to be highest (Wear et al. 2014).

The most accurate approaches to quantifying how FT *Eucalyptus* culture might affect water resources requires either direct measurements of changes in Q (e.g., from gauged watersheds) or scaled measurements of transpiration (e.g., sapflow or canopy conductance) with subsequent scaled effects on Q. At present, there are no data for FT *Eucalyptus* ET and Q in the United States and very limited data for nongenetically modified *Eucalyptus* species in the Southeast in general (Abichou et al. 2012). Our goal, therefore, is to estimate how changes in ET from planting FT *Eucalyptus* could affect Q using a multiscale generalized modeling approach, with parameters derived primarily from *E. grandis* in South America. As noted by Ferraz et al. (2013), the impacts of *Eucalyptus* on water resources needs to be examined both at the local scale and the landscape scale. Therefore, we asked the following two questions: How might FT *Eucalyptus* plantations affect overall local stand water balance in areas where FT *Eucalyptus* is most likely to be grown? And, how do the size and distribution of FT *Eucalyptus* plantations influence the water balance at varying spatial scales (e.g., local versus 12-digit Hydrologic Unit Code [HUC-12] scale)? Using USDA Plant Hardiness Zones 8b and greater, we further restricted the area of interest using the economic analyses of Wear et al. (2014), which determined the areas where FT *Eucalyptus* would probably be grown in the southern United States (Figure 1). We do not consider the effects of either irrigation or fertilization.

Methods

Assessing the potential impacts of FT *Eucalyptus* on water resources requires an analysis of all water budget components at multiple spatial levels and in the context of climate and other site characteristics that regulate soil water availability and storage. In its most basic form, the water balance of a forested watershed can be estimated as

$$Q = P - \text{ET} \pm \text{soil water storage}, \tag{1}$$

where Q is an estimate of excess water that contributes to streamflow, groundwater recharge, or soil water storage. Q is also termed "water yield" in the hydrology literature. Over long time periods (e.g., annual), the net soil water storage term is typically assumed to be 0, and the equation reduces to $Q = P - \text{ET}$. Depending on local topography, soils, and the geomorphic setting, a positive Q could contribute to streamflow or deep soil water storage and recharge, whereas a negative Q implies a cessation of streamflow and groundwater recharge. Expansion of FT *Eucalyptus* plantations would not be expected to change local P or the net change in soil water storage at annual time scales; hence, we focus primarily on how changes in ET might change Q.

Stand-Scale Water Balance

For estimating the stand-scale effects on Q, we assume that total stand-level ET is the sum of canopy interception and tree transpiration. After Equation 1, we subtracted ET from P to estimate annual water yield (Q). In this simple modeling scheme, we do not consider feedbacks of transpiration on soil moisture (e.g., with transpiration reducing soil moisture). Instead, we examine a range of soil moisture conditions—in situ measured for an open field and at field capacity. Our expectation was that a detailed process-based model would provide the best estimate of actual ET. To our knowledge, no physiological data are available for FT *Eucalyptus,* so we relied on physiological data and relationships from the published literature. We primarily used data for *E. grandis* (e.g., Mielke et al. 1999) for consistency between modeling approaches and because the data required to parameterize the models were readily available in the published literature.

We used a Penman-Monteith-based transpiration model to estimate transpiration (Ec) using Equation 2 and scaled it to the stand with leaf area estimates. The Ec model is based on the physiological processes of leaves in a tall canopy and can be used to estimate hourly water use by the stand. Model components include

$$E_c = \frac{1}{\lambda} \cdot \frac{sR_n + \rho c_p D g_a}{s + y(1 + \frac{g_a}{g_c})} \cdot t, \tag{2}$$

$$1/g_a = \{ln[(z - d)/z_O]\}^2/(k^2 u) \tag{3}$$

$$g_s = -0.024 + 0.00008\text{PPFD} - 0.156D + 0.129\psi_{pd} + 0.016T_a \tag{4}$$

$$\psi_{pd} = 0.33(\theta/\theta_{max})^{-0.57} \tag{5}$$

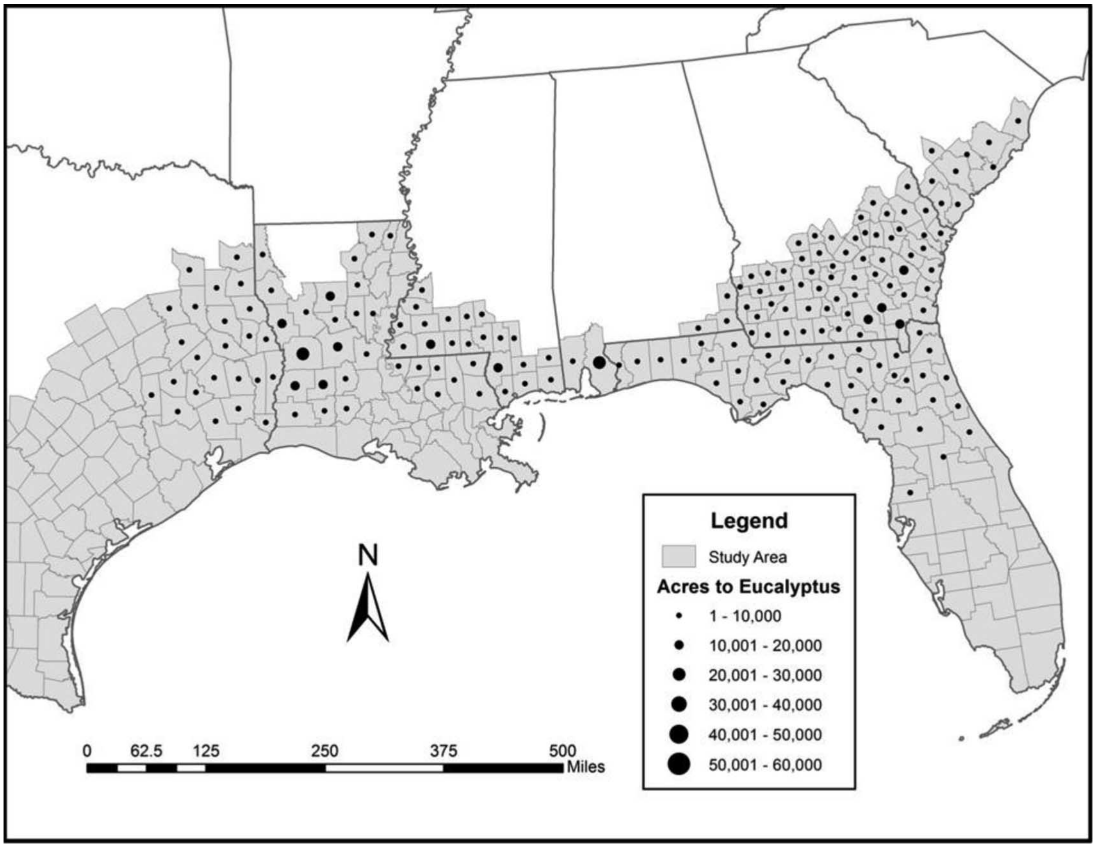

Figure 1. Forecasted area of FT *Eucalyptus* in the southeastern United States at year 10. The northern boundary represents counties in the upper limit of Plant Hardiness Zone 8b. For a detailed description of methods and assumptions, see Wear et al. (2014).

where E_c is canopy transpiration (mm hour^{-1}) and s is the slope of the saturation vapor pressure curve (mbar ° C^{-1}) at air temperature T_a (° C). R_n is average daylight canopy net radiation (W m^{-2}), ρ is air density (kg m^{-3}), γ is the psychometric constant (mbar ° C^{-1}), c_p is the specific heat of the air (J kg^{-1} ° C^{-1}), D is the vapor pressure deficit of the air (mbar), g_a is canopy aerodynamic conductance (m s^{-1}), g_c is canopy conductance to water vapor (m s^{-1}), λ is the latent heat of vaporization of water (J kg^{-1}), and t is the number of seconds in an hour (1,440) (s hour^{-1}). Canopy conductance, g_c, is given by $g_c = g_s \cdot \text{LAI}_{max} \cdot \text{fLAI}$, where g_s is the stomatal conductance (converted into m s^{-1} units), LAI_{max} is the maximum annual leaf area index (m^2 m^{-2}) for each year of the rotation, and fLAI is the fraction of maximum annual LAI (range 0–1). This latter term changes on a monthly basis and simulates the seasonal dynamics of leaf phenology (described below). The equation for g_s (mol m^{-2} s^{-1}) was taken from Mielke et al. (1999), where PPFD is photosynthetically active photon flux density (μmol m^{-2} s^{-1}) and ψ_{pd} is predawn water potential (MPa) estimated from the ratio of soil moisture content (θ, % v/v) and maximum annual soil moisture content (θ_{max}, % v/v). The soil moisture limitation on ψ_{pd} does not incorporate changes in soil moisture resulting from soil water uptake by *Eucalyptus* tree roots. Instead, θ reflects the net effects of climate, soils, and vegetation in the location of the open-field climate station (described below). Boundary layer conductance (g_a) was fixed at 0.083 m s^{-1}, based on a study by Hatton et al. (1992) on *Eucalyptus maculata* trees. The hourly estimates of E_c are then summed for all 24 hours in a day to estimate daily transpiration, summed for all days in a month to estimate monthly transpiration, and summed for all months in a year to estimate annual transpiration.

We applied this model to a hypothetical *Eucalyptus* plantation from initial planting through a full rotation. Maximum leaf area for *Eucalyptus* plantations is a function of precipitation and tree age and typically ranges from 3 to 5 m^2 m^{-2} (Stape et al. 2004, le Maire et al. 2011), although values as high as 8 m^2 m^{-2} have been reported in irrigated and fertilized *E. grandis* plantations (Myers et al. 1996). To model the dynamics associated with a developing stand, we began with an initial LAI = 2 m^2 m^{-2} at year 1 and then incrementally increased LAI by 0.5 m^2 m^{-2} per year, until the end of the rotation at age 7 when LAI = 5.0 m^2 m^{-2}. Intra-annual variation in LAI was simulated based on maximum annual LAI and the monthly dynamics of two plantations in Brazil (Hubbard et al. 2010).

Climate data used in the *Ec* model were obtained from five open-field climate stations maintained by the Natural Resources Conservation Service (NRCS) (NRCS 2008–2012) as part of the Soil Climate Analysis Network (SCAN). Climate data at each station were available for a variable number of years; we used data from five sites across five states that had at least 18 months of data available to run the model. Sites were located across the southeastern Gulf Coastal Plain in Texas, Alabama, Georgia, Florida, and Mississippi (NRCS SCAN stations 2016, 2180, 2027, 2009, and 2082, respectively) (Figure 2). Data consisted of hourly measurements of standard climate variables (e.g., air temperature, relative humidity, solar radiation, and wind speed) used to estimate plant water use, as well as soil moisture measured in a vertical array over five depths (depths 5–100 cm) at the climate station (Table 1). To obtain an upper limit for ET, we also simulated ET without soil moisture constraints on g_s by setting θ to θ_{max} for all time periods; i.e., predawn water potential was always equal to 0.33 MPa (see Equations 4 and 5). This would

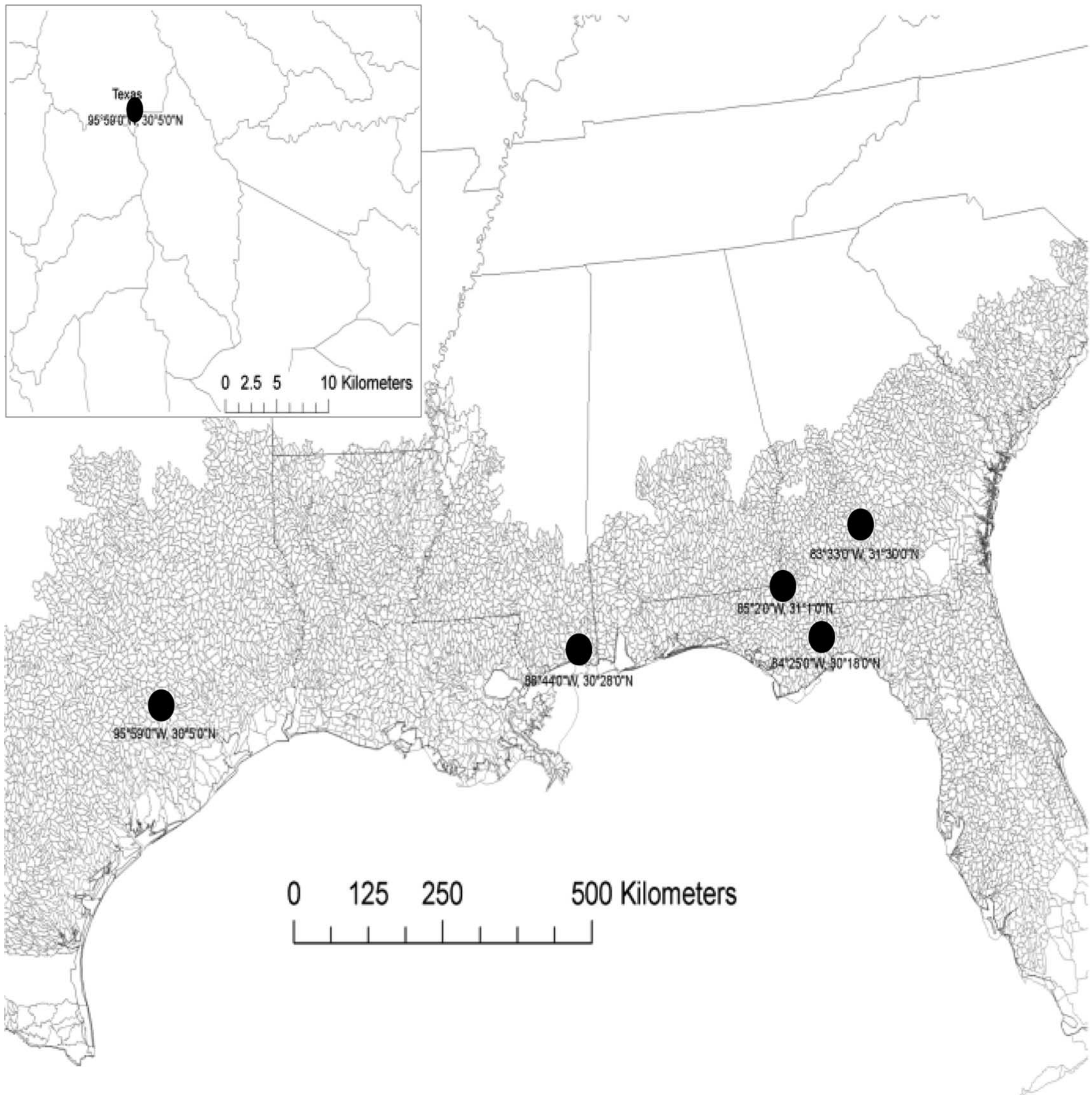

Figure 2. Locations of stand-level studies overlain on the 12-digit HUC watersheds. The expanded view provides a visual context for the scale of a 12-digit HUC.

Table 1. Environmental conditions at the five study sites.

Location	Soil moisture (%, v/v)	Precipitation (mm)	Air temperature (° C)	Net radiation ($W\ m^{-2}$)
Alabama	15.6	1,479	20.6	201
Florida	5.1	1,375	20.5	155
Georgia	13.1	1,063	19.7	190
Mississippi	25.3	1,553	18.1	183
Texas	21.2	779	19.9	196

Data are annual daily means (soil moisture, temperature, and net radiation) and annual total (precipitation) obtained from the NRCS field sites described in the Methods section.

represent a well-watered soil such as what might occur in areas with high and well-distributed rainfall, with irrigation, or with year-round access to groundwater for roots. To estimate canopy interception (I_c), we used an empirical interception model ($I_c = 0.11 \cdot P$) developed for a *E. grandis* hybrid plantation (Soares and Almeida 2001), where P is annual precipitation in mm. Evapotranspiration was estimated for all years at each site, and a mean for each year of stand development was calculated.

Watershed-Scale Water Balance

Although a detailed process-based model is often a better approach for simulating complex hydrologic processes and estimating actual ET, the intensive data requirements of process-based models preclude this approach at larger spatial scales, such as the USDA Plant Hardiness Zone 8b and greater in our study. Hence, we used a parsimonious, large-scale, monthly water balance model (WaSSI) (Sun et al. 2011b, Caldwell et al. 2012) to evaluate the potential effects of planting *Eucalyptus* at the watershed scale. This model was chosen because of its ease of use and performance in similar applications assessing the implications of changing land cover on water balance. Complete WaSSI model details are available in Sun et al. (2011b) and Caldwell et al. (2012); thus, only a brief explanation of the modifications required to use WaSSI to assess *Eucalyptus* ET is presented here.

WaSSI simulates actual ET, soil water storage, water yield, and streamflow at the watershed outlet at a monthly time step. Each watershed was divided into 10 possible land cover types based on the 2006 National Land Cover Dataset (NLCD) (Fry et al. 2011): deciduous forest, evergreen forest, mixed forest, crop, grassland, shrubland, wetland, water, urban, and barren. WaSSI predicts the

ET of each land cover type within each watershed from empirical relationships between actual ET (AET) versus climate variables, stand LAI, and potential ET (PET) developed using multisite eddy covariance ET measurements for a variety of land cover types (Sun et al. 2011a). This estimate of AET is then constrained by available soil moisture in WaSSI using algorithms of the Sacramento Soil Moisture Accounting Model (Burnash 1995). Accurate predictions of AET for the various land covers are a critical component of the overall model; however, no models are available for *Eucalyptus* growing in the Southern United States. For this analysis, monthly AET values for *Eucalyptus* were predicted using empirical relationships between AET and PET, *P*, and LAI. These relationships were developed using measured AET, LAI, and climate variables for *E. grandis* acquired from an eddy covariance study site in Brazil (Cabral et al. 2010). The *Eucalyptus* equation took the following form

$$\text{AET} = -270.3 + \text{LAI} \cdot (116.6 + 0.056\ \text{PET} - 0.455 \cdot P_i) + 0.168 \cdot P_{i-1} + 1.374 \cdot P_i \quad (6)$$

with the data fitting the model well (adjusted $R^2 = 0.81$; $P < 0.001$; root mean square error = 21 mm month^{-1}). In Equation 6, PET is estimated using a formulation published by Hamon (1963) based on mean air temperature (T) and sunshine hours, and P_i and P_{i-1} are the current and previous month's total precipitation, respectively. All units are in mm per month.

To characterize how different land covers influence water balance at the 12-digit HUC watersheds, land cover-specific LAI data were derived from Moderate Resolution Imaging Spectroradiometer (MODIS) remote sensing products (1,000-m spatial resolution), and water use was driven by land cover-based variations in LAI (Sun et al. 2011a). Although the WaSSI model does not use a separate ET model to estimate ET for each land cover in a watershed (with the exception of *Eucalyptus*), the WaSSI-ET model does consider the effects of LAI (magnitude and seasonal dynamics) on water use.

Based on the results from sensitivity analyses, the empirical AET model in Equation 6 was not sensitive to variations in air temperature for two reasons: most likely because the range of air temperature data from the Brazil site used to develop the empirical relationship was narrow and generally warmer than that observed across the southeastern US region and because the model only indirectly accounts for T through PET. As a result, AET estimates in the winter months were high, especially when T_a was ≤18° C and P was large. To reduce AET estimates under these conditions, we set AET equal to 1.6 · PET when predicted AET using Equation 6 was greater than PET and T_a was ≤18° C. The 1.6 correction factor, which represents the maximum ratio of ET and PET during wet and cool periods for *Eucalyptus* in Brazil (Cabral et al. 2010) was within the range (e.g., 1.4–2.0) of previous studies examining AET/PET relationships in southern US forests (Lu et al. 2009, Rao et al. 2011). We also compared monthly AET predictions generated with the stand-level process-based model with those of the WaSSI large-scale empirical model and found that they were well correlated with no obvious biases (Figure 3). This added confidence to our AET estimates derived from the empirical model and subsequent estimates of the implications for large-scale water balance.

To assess the watershed-scale implications of planting *Eucalyptus* at the five study locations (Figure 2) where we used the Penman-Monteith-based modeling, we identified the HUC-12 watersheds at each location. The HUC-12 is the watershed classification system with the highest spatial resolution (~90 km^2) currently available for

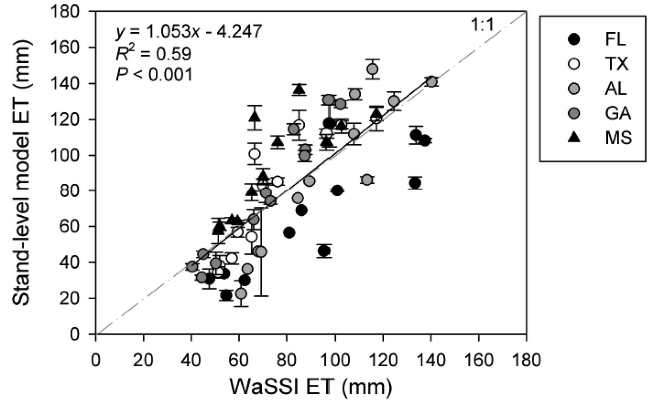

Figure 3. Comparison of the ET-based stand-level model and the WaSSI large-scale model.

the continental United States. There are about 17,000 HUC-12 watersheds in our study region. We applied WaSSI under current land cover conditions based on the 2006 NLCD for the period 1999–2010 to generate baseline monthly and annual water balances for these five watersheds. Next, we replaced varying proportions of existing conifer forest cover (Table 3) (identified as the most likely land cover type to switch to *Eucalyptus* by Wear et al. 2014) with 3, 10, 20, and 50% *Eucalyptus* and recalculated the water yield for each scenario. We also included a scenario where 100% of the vegetation cover (i.e., grass, forest crop, etc.) was replaced by *Eucalyptus* to demonstrate the model sensitivity and potential effects under the most extreme level of conversion. The potential effects were evaluated by quantifying the absolute (mm year^{-1}) and percentage changes in mean annual Q from baseline conditions of current land cover. In all cases, we used a maximum LAI value for *Eucalyptus* of 4.0 $\text{m}^2\ \text{m}^{-2}$ to represent an older stand with moderate productivity. Additional data sets required for the model included monthly precipitation and mean air temperature (PRISM Climate Group 2010), LAI (Zhao et al. 2005), and soil properties. These national scale gridded data sets were downloaded and rescaled to the HUC-12 watershed as described in Sun et al. (2011b) and Caldwell et al. (2012).

Using the same approach, we expanded the analysis to include all areas in Plant Hardiness Zone 8b and greater, excluding areas identified as highly unlikely to support *Eucalyptus* as a result of biophysical or socioeconomic constraints (Wear et al. 2014). For example, Wear et al. (2014) excluded areas within zone 8b that would require irrigation on the basis of high cost. We simulated replacement of 3, 10, 20, and 50% of the conifer land cover with *Eucalyptus* (i.e., 10–20% conversion from pine to *Eucalyptus* represents the upper range and likely land cover that *Eucalyptus* would replace (Wear et al. 2014) and used the WaSSi model to assess impacts on Q.

Results and Discussion

Stand Scale

Climate

The five locations used in our simulations of FT *Eucalyptus* water balance represented a wide range of climatic conditions (Table 1). The mean annual precipitation averaged over the years used for simulation ranged from about 780 mm year^{-1} for the site in Texas to about 1,550 mm year^{-1} for the site in Mississippi. Indeed, the low precipitation value for the Texas location is slightly below the

Table 2. Annual evapotranspiration for *Eucalyptus* in Brazil and for major forest types in southeastern United States.

Forest type	Evapotranspiration (ET) (mm)	Precipitation (P) (mm)	ET/P	Reference(s)
Eucalyptus plantation (clonal *Eucalyptus grandis* × *Eucalyptus Urophylla*), 2–4 yr old, São Paulo State, Brazil	1,179 (1,124–1,235)	1,329 (1,280–1,377)	0.88 (0.82–0.96)	Cabral et al. (2010)
Eucalyptus plantation (hybrid of *E. urophylla* and *E. grandis*), 2–6 yr old, spacing of 3.00 × 2.75 m, São Paulo State, Brazil	1,101 (943–1,364)	1,308 (1,150–1,601)	0.84 (0.81–0.89)	Lima et al. (2012)
Eucalyptus plantation (hybrid of *E. urophylla* and *E. grandis,* different clone), 0–2 yr old, spacing of 6.00 × 1.40 m, São Paulo State, Brazil	1,099 (949–1,240)	1,601 (1,537–1,716)	0.69 (0.55–0.80)	Lima et al. (2012)
Loblolly pine plantation, 16 yr old, coastal North Carolina	1,087 (1,011–1,226)	1,238	0.88	Sun et al. (2010)
Loblolly pine plantation, 4 yr old, coastal North Carolina	838 (755–885)	1,274	0.66	Sun et al. (2010)
Loblolly pine plantation, 4 yr old, coastal North Carolina	895 (702–1,078)	1,152	0.78 (0.73–0.94)	Diggs (2004)
Loblolly pine plantation, 15 yr old, coastal North Carolina	988 938 (after thinning 1/3 of basal area)	1,098	0.9	Grace et al. (2006a, 2006b)
Loblolly pine plantation, 14–30 yr old, coastal North Carolina	997 (763–1,792)	1,538 (947–1,346)	0.65	Amayta et al. (2006)
Slash pine (*Pinus taeda* L.) plantation, full rotation, Florida (extreme drought years)	754 (676–832)	883 (811–956)	0.85	Powell et al. (2005)
Pine flatwoods, Bradford Forest, Florida	1,077	1,261	0.87	Sun et al. (2002)
Deciduous hardwoods, Coweeta, North Carolina	779	1,730	0.47	Sun et al. (2002)
Mixed pine and hardwoods, Santee Experimental Forest, South Carolina	1,133	1,382	0.82	Lu et al. (2003)
White pine (*Pinus strobus* L.), Coweeta, North Carolina	1,291	2,241	0.58	Ford et al. (2007)

US values are adapted from Sun et al. (2010). Values in parentheses are ranges.

Table 3. Current land cover for the 12-digit HUCs associated with the five study locations.

Location	HUC	Current land cover (2006)								
		Crop	Urban	Grassland	Deciduous	Evergreen	Wetland	Shrubland	Mixed forest	Water
		(%)								
Alabama	31300040801	49	4	4	7	17	9	7	2	2
Florida	31200010702	4	7	5	1	35	39	5	4	0
Georgia	31102040105	34	21	7	6	14	14	0	4	0
Mississippi	31700090704	4	14	5	0	28	23	25	0	1
Texas	120401020101	75	9	2	3	1	4	4	0	0

Land cover sources: 2006 National Land Cover Database for the Conterminous United States (Fry et al. 2011). Rows sums of >100 or <100 are due to rounding.

precipitation limit (i.e., 800 mm $year^{-1}$) where FT *Eucalyptus* plantations would be expected to be viable. The nearly 2-fold variation in precipitation influences soil θ and available water for transpiration; however, θ is also affected by soil textural characteristics that influence water holding capacity. As a result, measured soil moisture ranged from 5.1 to 25.3% across the sites; it was lowest at the Florida location and greatest at the Mississippi location. Mean annual air temperature ranged from 18.1 to 20.6° C, and net solar radiation ranged from 155 to 201 W m^{-2}.

ET Estimates

Only variations in ET reflect differences in climatic conditions and soil moisture because assumptions about leaf area and stand development patterns (i.e., an increase in LAI from 2.0 to 5.0 m^2 m^{-2} by 0.5 increments from age 1 to age 7) were consistent across the five study locations (Figure 4A). In ranking locations, the highest ET was predicted for the Mississippi and Alabama locations, the lowest ET was predicted for the Florida location, and the ETs for Texas and Georgia locations were intermediate. As would be expected, stand-level ET increased with stand age and reflected our assumed patterns of leaf area development. By the end of the rotation (age 7; LAI = 5 m^2 m^{-2}), our predictions of annual ET rates ranged from about 900 mm $year^{-1}$ in Florida to >1,200 mm $year^{-1}$ in Mississippi and Alabama. We did not develop physically based ET models for other land cover types because a large number of stand-scale ET estimates already existed for alternative land covers in the southeastern United States (Table 2). Our predictions for FT *Eucalyptus* ET values were 1.5- to 2-fold greater than estimates for old fields (460–650 mm; Stoy et al. 2006), mature deciduous hardwood forests (480–640 mm; Stoy et al. 2006), and loblolly pine plantations (560–740 mm; Stoy et al. 2006) in the Piedmont region of the southeastern United States, and for crops such as cotton (386–397 mm for no irrigation and 739–775 mm for irrigated; data not shown in Table 2) (Howell et al. 2004), but were comparable to those for some slash and loblolly pine plantations in the Coastal Plain region of the southeastern United States (676–1,226 mm; Gholz and Clark 2002, Powell et al. 2005, Stoy et al. 2006, Sun et al. 2010). We are aware of only one study in which *Eucalyptus* ET was quantified in the United States. In that study, Abichou et al. (2012) estimated an average annual ET of 1,086 mm (81% of precipitation) for *Eucalyptus amplifolia* in the Florida Panhandle using weighing lysimeters and a constructed soil system. If site

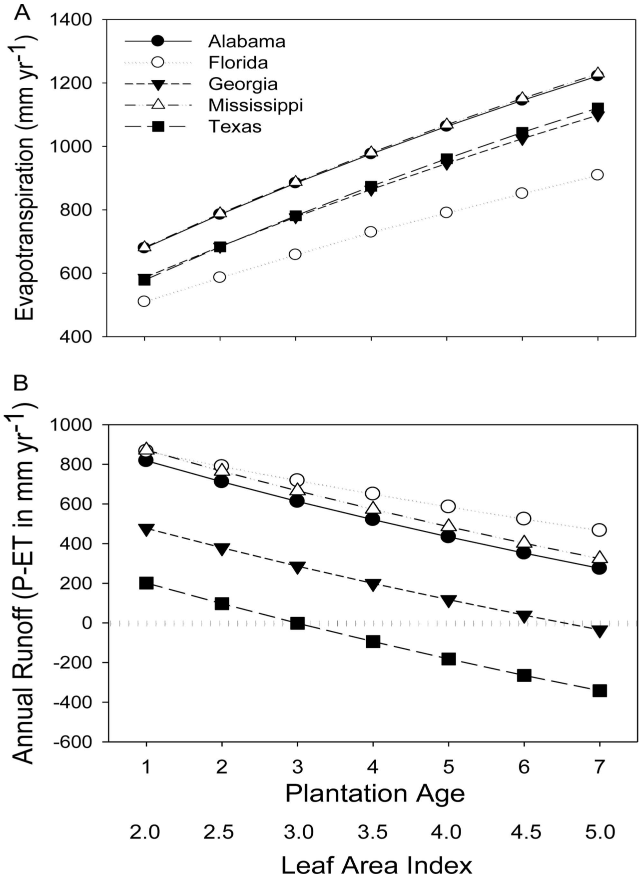

Figure 4. Annual ET (A) and annual runoff or *Q* (B) predicted from the process-based model for the five intensive study locations. The model does not incorporate physiological or structural adjustments that occur when annual ET exceeds *P* (i.e., leaf area reduction, access to deep soil water, etc.), so predicted runoff is negative for the Texas site when LAI = >3.0. Because "negative runoff" is not possible, these data should be interpreted as runoff = 0.

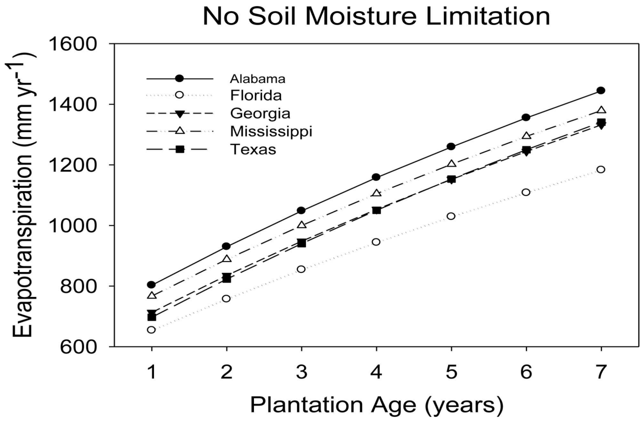

Figure 5. Estimates of FT *Eucalyptus* evapotranspiration without soil moisture limitations on stomatal conductance.

conditions (e.g., soil nutrients, disturbances, and precipitation) (Stape et al. 2004) preclude attainment of LAI = 5 $m^2\ m^{-2}$ and lower maximum LAI values (e.g., 3–4 $m^2\ m^{-2}$) result, annual ET estimates ranged from about 600 mm (Florida) to 850 mm (Alabama and Mississippi), which were well within the range of what has been observed for late-rotation pine plantations in the southeastern United States (Sun et al. 2010). When soil moisture controls on stomatal conductance were removed by assuming an unlimited supply of soil water, ET values were on average about 20% higher overall, with the highest ET exceeding 1,400 mm $year^{-1}$ in year 7 at the Alabama location (Figure 5). These wet soil conditions would probably be comparable to areas where high ET (e.g., > 1,000 mm $year^{-1}$) has been observed for loblolly and slash pine plantations (Gholz and Clark 2002, Sun et al. 2010). In these cases, the energy available to drive transpiration is the primary limiting factor, rather than soil water resources.

Although we focused on comparing differences in maximum expected ET between *Eucalyptus* and pine stands, an additional consideration is the difference in cumulative water use over multiple rotations (e.g., *Eucalyptus*) versus a single rotation (e.g., pine). Ferraz et al. (2013) suggested that multiple short rotations would have a larger cumulative effect on ET (and hence *Q*) compared with that of longer rotations of pure or mixed *Eucalyptus* stands in Brazil, primarily because ET declines considerably as *Eucalyptus* stands age. Although long-term data are limited, there is little evidence to suggest that ET declines over rotation length time periods (e.g., 20–30 years) in pine stands in the South (e.g., Amatya and Skaggs 2011, Ford et al. 2011). This long period of relatively stable "maximum ET" in pine stands may offset the cumulative effects of multiple rotations in *Eucalyptus* suggested by Ferraz et al. (2013).

Stand Water Balance

Estimates of stand water balance ($Q = P - \text{ET}$) declined as ET increased over time (Figure 4B). For three of the locations, *Q* remained positive over the full rotation. However, at the Texas site, estimates of *Q* reached 0 by age 3 (LAI = 3 $m^2\ m^{-2}$), and *Q* reached 0 at the Georgia site at age 7 (LAI = 5.0 $m^2\ m^{-2}$). However, if ET exceeds precipitation, trees would experience considerable water stress, and physiological adjustments would reduce ET such that *Q* would not be less than 0 (as shown in Figure 4B). For example, trees would need to either access water not supplied through precipitation (i.e., access to deep water sources) to maintain ET, reduce ET through shedding leaves, or adjust stomatal and hydraulic properties (Whitehead and Beadle 2004). Leaf area reduction could occur through tree mortality or fewer leaves per tree, a likely result during drought conditions or with planting in low rainfall areas. These drought avoidance adjustments are too complex (and unknown for FT *Eucalyptus*) to be included in our modeling; however, the ability of *Eucalyptus* to survive sudden or prolonged drought is well recognized (Whitehead and Beadle 2004) and provides a mechanism for persistence in the drier regions of Plant Hardiness Zone 8b and greater. If our model and assumptions are correct, these results indicate the potential for the complete elimination of groundwater recharge or surface water flows in areas with low annual precipitation or during drought years in areas with higher average annual rainfall. It should be noted that predicting *Q* with this simple water balance approach (i.e., $P - \text{ET}$) also suggests complete elimination of flow for many other forest types listed in Table 2 under low rainfall conditions (e.g., ~800 mm $year^{-1}$). In contrast, temporal patterns in areas with higher rainfall suggest that although *Q* declines as a stand develops (Figure 4B), site water balance remained positive throughout the rotation.

Intra-Annual Patterns

At the monthly scale, ET estimates show a distinct seasonal pattern. Across all sites, peak ET occurred in either June or July when

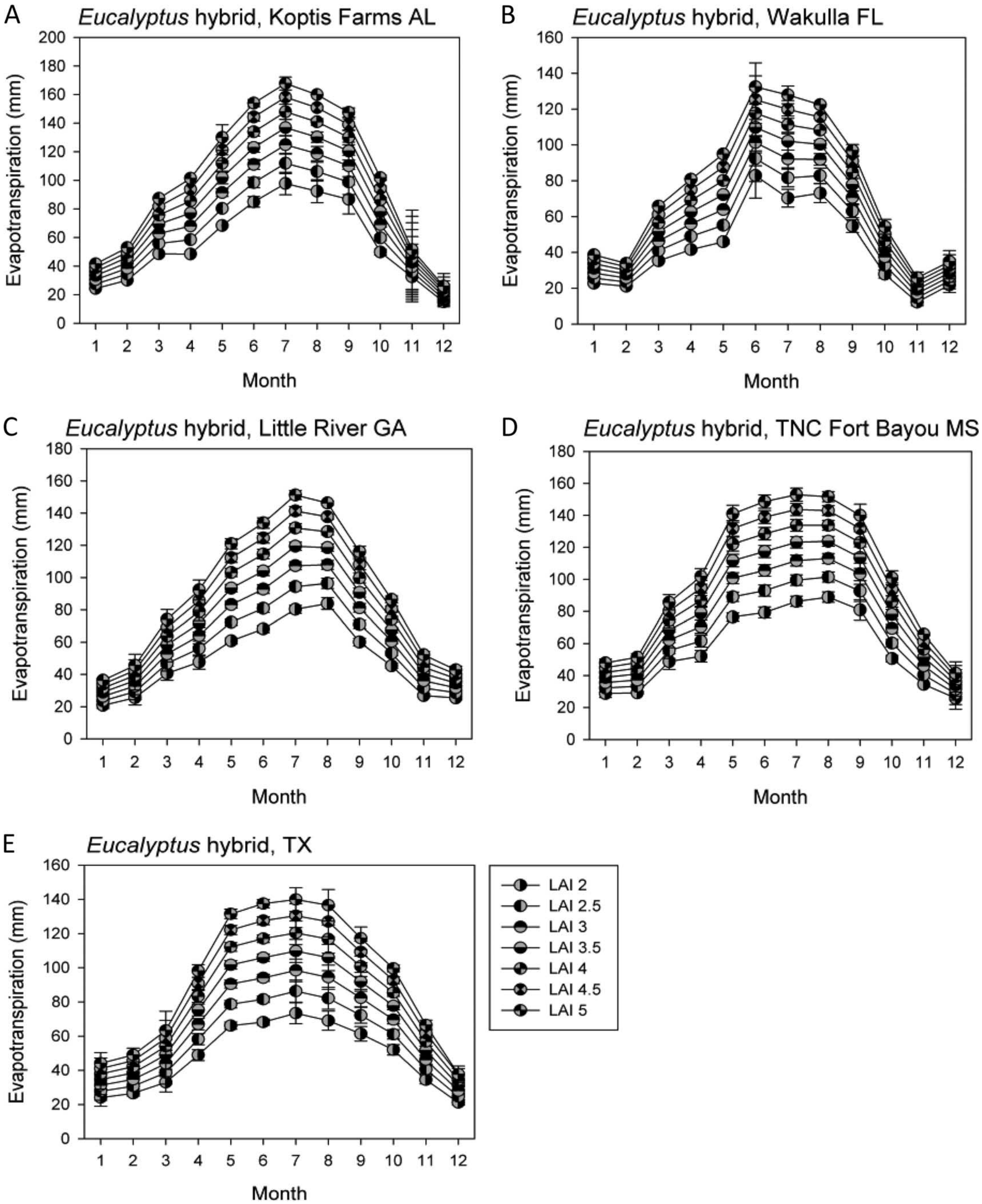

Figure 6. (A–E) Monthly total evapotranspiration (error bars denote SEM) simulated across all years of climate and over 7 years of stand development for five sites. Stand development is represented as increases in LAI from 2 to 5 $m^2\ m^{-2}$.

the potential evaporation energy is the highest (Figure 6A–E). This pattern coincides with the timing of maximum stand LAI and when climatic driving variables are most favorable to drive ET. These peak values are well within the range of observations for other *Eucalyptus* species across the globe (Whitehead and Beadle 2004). Estimating Q by $P - \mathrm{ET}$ may violate the assumptions of soil water storage, and thus we do not apply this approach at subannual time scales. Therefore, we are unable to quantify seasonal variations in Q using this approach. However, these seasonal patterns in predicted ET suggest that under evenly distributed precipitation patterns, Q probably would be most affected during the summer months when soil water deficits occur.

Watershed Scale

The impact of planting FT *Eucalyptus* at larger spatial scales will vary, depending on the hydrologic setting (e.g., high versus low rainfall) and the type and amount of land cover being replaced. To include the influence of land cover, one of our tasks was to quantify ET for current land cover types across the region. At the five locations used in the process-based modeling, current land cover within the associated 12-digit HUC watersheds varied greatly (Table 3).

The interactions among hydrologic setting, current land cover, and the amount of land cover changed were examined by predicting changes in absolute and relative water yield across a range of scenarios that converted conifer forest to *Eucalyptus* at

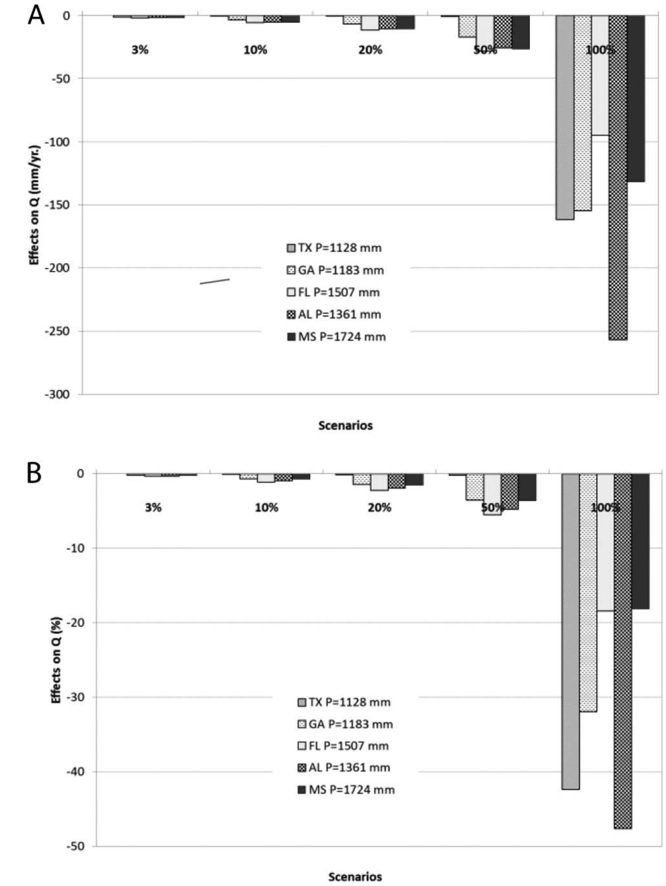

Figure 7. Simulated effects of planting *Eucalyptus* at varying levels of conversion on Q. Shown are absolute change (mm year^{-1}) (A) and relative change (%) in water yield (B) for the five watersheds where the stand-level modeling sites are located. Percentages on the bar graphs represent the amounts of conifer land cover converted to FT *Eucalyptus* within the watershed.

varying proportions. As expected, large changes in Q (amount and percentage) were predicted when all of the vegetation within the watershed was converted to FT *Eucalyptus* (Figure 7A and B); however, there were substantial differences in the magnitude of response among locations. For absolute changes in flow, the responses varied from about -250 mm year^{-1} (-48%) at the Alabama location to about -100 mm year^{-1} (-18%) at the Florida location (Figure 7A and B). These changes are comparable to those predicted at the stand scale. Based on the economic analysis (Wear et al. 2014), adoption of FT *Eucalyptus* would probably occur at a much smaller scale. For example, when only 3% of the vegetative cover in the watersheds was converted to FT *Eucalyptus* (Figure 7A and B), changes in Q (amount or percentage) were very small (e.g., $<$5 mm and $<$1%) across all study areas. In short, responses of this magnitude would probably not be measurable with streamflow gauges at a large scale, are unlikely to negatively impact streamflow or groundwater recharge, and are well within the errors associated with this type of model-based approach. However, as noted in the previous section, measurable and negative local-scale impacts could occur immediately downstream of FT *Eucalyptus* plantations. At greater levels of change (e.g., 20 and 50%), impacts on Q were more evident. For example, when 50% of the conifer cover was converted to FT *Eucalyptus* (Figure 7A and B), Q decreased by as much as 25 mm year^{-1} (about a 5% reduction) (Figure 7B). Because of the low amount of existing conifer land cover at the Texas location (Table 3), it was always the least responsive to conversion to FT *Eucalyptus*. For all areas in Plant Hardiness Zone 8b and greater, simulations assuming either a 10% (Figure 8A and B) or 20% (Figure 8C and D) replacement of conifer land cover with FT *Eucalyptus* suggested minimal impacts on Q (i.e., $<$24 mm of absolute Q; $<$10% change in percent Q) at the HUC-12 scale. At a 50% replacement of conifer cover with FT *Eucalyptus* (Figure 8E and F), simulations suggested that reductions in Q of $\sim$100 mm were possible, especially in the Florida Panhandle region and in parts of Louisiana, Alabama, and Texas.

We emphasize that these results are based on the assumption of an average LAI = 4.0 m^2 m^{-2} across the entire HUC-12 watershed, which is representative of an older stand nearing the end of the rotation (assumed to be 7 years). As a result, our analyses and interpretations reflect what might occur under a near "maximum impact" scenario. Lower LAIs (reflective of factors such as younger stands, lower density, or poor quality sites) would lessen these effects.

Implications and Uncertainties

The effects of planting FT *Eucalyptus* on Q will vary by location and the hydrologic conditions of the planting site and surrounding area. Positive (i.e., Q increases after planting FT *Eucalyptus*) or negative (i.e., Q decreases after planting FT *Eucalyptus*) impacts will also depend on the change in ET relative to the land cover before *Eucalyptus* establishment. To illustrate, we compare ET values of *Eucalyptus* with those for alternative options for wood fiber production such as pine plantations. Estimates of planted pine ET range from about 750 to 1,200 mm year^{-1}, with the latter being observed in areas where soil water is plentiful (Gholz and Clark 2002, Powell et al. 2005, Stoy et al. 2006, Sun et al. 2010). At LAI = 4 m^2 m^{-2}, predicted *Eucalyptus* ET ranges from 790 mm year^{-1} at the Florida site to 980 mm year^{-1} at the Mississippi site, within the range for pine stands. This result suggests that contributions to streamflow/recharge could be equal to or reduced by as much as to 130 mm year^{-1} relative to those for pine near the end of the rotation or on sites where LAI is below the maximum. As a percentage of precipitation across the five study areas, this equates to a range of 9% (precipitation = 1,500 mm year^{-1}) to 16% (at precipitation = 800 mm year^{-1}). At *Eucalyptus* LAI = 5 m^2 m^{-2}, ET ranges from 909 mm year^{-1} (Florida) to 1,229 mm year^{-1} (Mississippi). Compared with published values for mature pine stands in the southern United States that are also at maximum ET (i.e., peak LAI has been attained) (Vose et al. 1994), modeled estimates for *Eucalyptus* ET are generally comparable to those for pine stands where annual rainfall is plentiful; however, our model predicts that *Eucalyptus* ET is greater than that for pine at lower rainfall amounts (Figure 9A). For example, we predicted that the two *Eucalyptus* sites located in areas with lower rainfall would use 100% of annual rainfall (i.e., ET/$P \geq 1$) (Figure 9B), whereas ET/P based on observed data was always $<$1 for pine stands. Under these conditions, reductions in contributions to streamflow or groundwater recharge of about 0–500 mm year^{-1} are possible compared with those for pine. As a percentage of precipitation, this equates to a range of 33% (precipitation = 1,500 mm year^{-1}) to 63% (precipitation = 800 mm year^{-1}). The implications for these reductions in streamflow and/or groundwater recharge depend on the hydrologic setting and the amount of land area planted in FT *Eucalyptus.* For

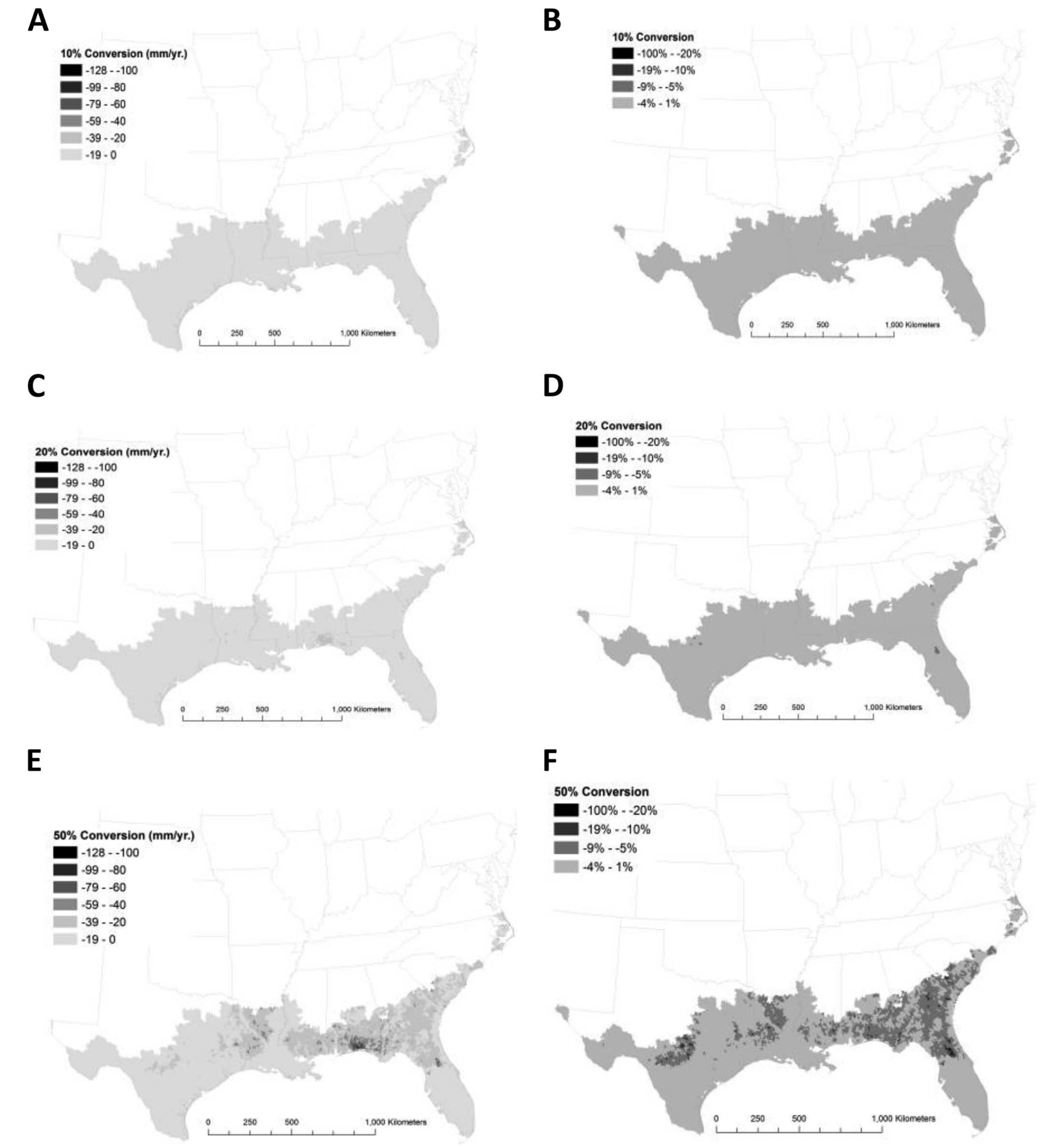

Figure 8. Regional analysis simulating the impact on *Q* (absolute change in mm year^{-1} and percent change) of replacing 10% of the conifer cover (A and B), 20% of the conifer cover (C and D), and 50% of the conifer land cover (E and F) with FT *Eucalyptus* for all of the 12-digit HUC watersheds in the southern region of Plant Hardiness Zones 8b and greater.

example, negative impacts might arise when planting in areas where (1) precipitation is limited, (2) where dry years are likely, (3) where the ratio of *P*/PET is low, (4) where planting occurs in headwaters, (5) or close to streams with low annual baseflow.

These estimates are the best approximations given limited knowledge, and they should be viewed in the context of an incomplete understanding of the rooting characteristics, leaf phenology, and ecophysiology of FT *Eucalyptus* in the southeastern United States that could potentially affect the model-based estimates of ET. For example, model parameters were primarily derived from *E. grandis*, and it is uncertain whether FT *Eucalyptus* parameters would be comparable. Furthermore, we do not know how leaf area or

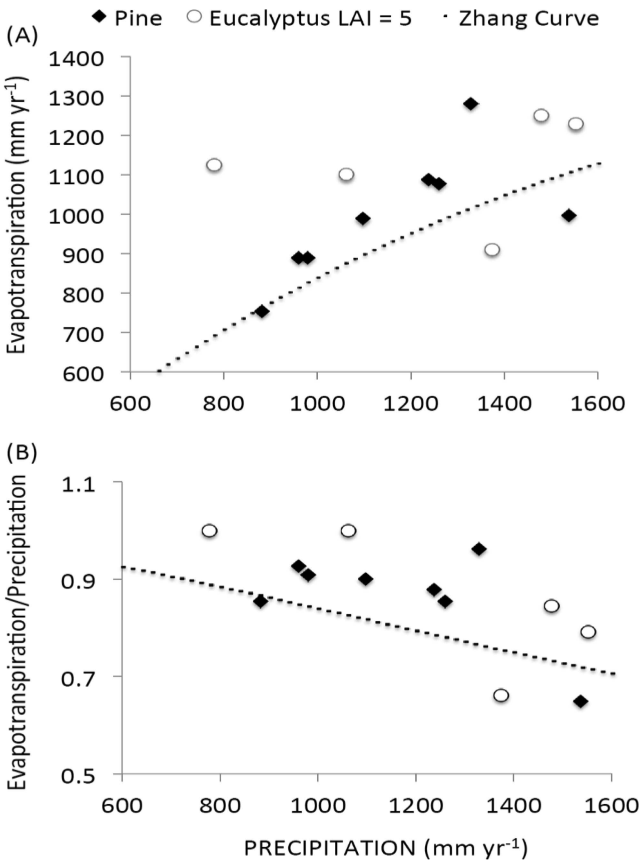

Figure 9. Comparison of evapotranspiration (A) and ET/*P* (B); if ET/*P* values are >1, we assigned a value = 1 to reflect 100% use of annual precipitation in ET from modeled *Eucalyptus* in this study (age = 7; LAI = 5) versus estimates for mature pine stands in the southern United States (mean values for loblolly and slash pine are derived from Table 2 and Knight et al. 1994). Data are graphed versus precipitation to standardize for precipitation differences. The Zhang curve (dotted lines) is derived from Zhang et al. (2001), who provided a generalized model for the relationship between *P* and ET for forests.

stomatal conductance (g_s) in FT *Eucalyptus* would recover after a freeze event and if either of these would affect the effective growing season length. In addition, deep rooting could allow FT *Eucalyptus* to maintain higher leaf water potentials and g_s under dry conditions relative to those of pine or other native species.

Assessing and interpreting impacts at larger spatial scales is an extremely challenging task because they depend on the hydrologic setting, current land cover and its water use, and the amount of land cover converted. Our modeling approach addresses all of these variables at a coarse scale and represents a "best approximation" based on the available data. At the scale of conversion indicated by the economic analysis (e.g., <20% conversion of conifer cover to FT *Eucalyptus*) (Wear et al. 2014), our analysis (using an average of LAI = 4 m^2 m^{-2} across the entire watershed) suggests that at the scale of the 12-digit HUC, effects on *Q* would be negligible. At lower LAIs (i.e., early rotation), impacts would be even lower. Localized reductions in water resources may occur immediately downstream of FT *Eucalyptus* plantations even at low land cover conversion rates. In contrast, if economic conditions promoted large-scale conversion of existing land cover (e.g., 50% of current conifer cover) to FT *Eucalyptus,* then regional reductions in *Q* could be realized in many areas of Plant Hardiness Zone 8b and greater. Areas where changes are anticipated to be the greatest include the Florida Panhandle, South Alabama, southwest Georgia, Louisiana, and southern Mississippi (Figure 8E and F).

Our model-based analysis represents our best approximation based on currently available data; however, to make this approximation, we had to assume several conditions, which we summarize below:

1. Physiological (e.g., stomatal conductance) and stand structure data (e.g., LAI amount, season dynamics, and development over time) from *E. grandis* (and other *Eucalyptus* species) growing in other regions of the world are applicable to FT *Eucalyptus* growing in USDA Plant Hardiness Zone 8b and greater.
2. The stand-level model was a sufficient representation of how FT *Eucalyptus* would respond to climatic and soil driving variables at the five study locations.
3. The empirical AET model (Equation 6) developed from an eddy covariance tower in Brazil was applicable to FT *Eucalyptus* growing in USDA Plant Hardiness Zone 8b and greater.
4. Stand LAI = 4–5 m^2 m^{-2} is a reasonable estimate for commercial stands of FT *Eucalyptus* growing in USDA Plant Hardiness Zone 8b and greater.

In addition to these assumptions, biophysical models at all scales were limited by imperfect knowledge and simplifications of processes, parameters, and driving variables and by limits to the accuracy and precision of climate driving variables such as precipitation and air temperature. Furthermore, these results must be viewed in the context of the hydrologic setting of the area of the plantation. Key physical features such as soil texture, topography, existing drainage networks and road systems, and groundwater depth can either mitigate or exacerbate responses. Future climate variability, especially an increased frequency and severity of drought, may make some areas much more sensitive to the effects of higher ET in the future. Our models were not appropriate for capturing responses during extremely severe or prolonged climate years (e.g., drought) due to a lack of model sophistication and feedback on the physiological and structural responses of FT *Eucalyptus.* These assumptions and uncertainties reinforce the need to obtain empirical measurements to validate (or reject) model projections.

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