Conversion of natural forests to managed forest plantations decreases tree resistance to prolonged droughts

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Rationale and Objectives

Throughout the southern U.S., past forest management practices have replaced large areas of native forests with loblolly pine (*Pinus taeda*) plantations, potentially resulting in changes in forest resilience to extreme weather and changes in climate. Uncertainty still remains about the response of planted versus natural species to drought across the geographic range of Southern forests. Utilizing an instrumented cluster of unmanaged stands, 85-130 year-old hardwood stands, and managed, 7-20 year-old loblolly pine plantations in coastal and Piedmont areas of North Carolina (Table 1), tree water use, cavitation resistance, whole-tree hydraulic (K_{tree}) and stomatal (G_s) conductances were measured in four sites covering representative forests growing in the region. We also used a hydraulic model (Sperry et al. 1998) to predict the resilience of those sites to extreme soil drying. Our objectives were to determine: (1) how ecosystem type affects the water uptake limit that can be reached under drought; and (2) the influence of stand species composition on critical transpiration that sets a functional water uptake limit under drought conditions.

The broadleaved deciduous species of the Piedmont stand had the highest resistance to embolism (Fig. 1).
However *Pinus taeda* roots were less resistant to embolism than almost any of the deciduous species!

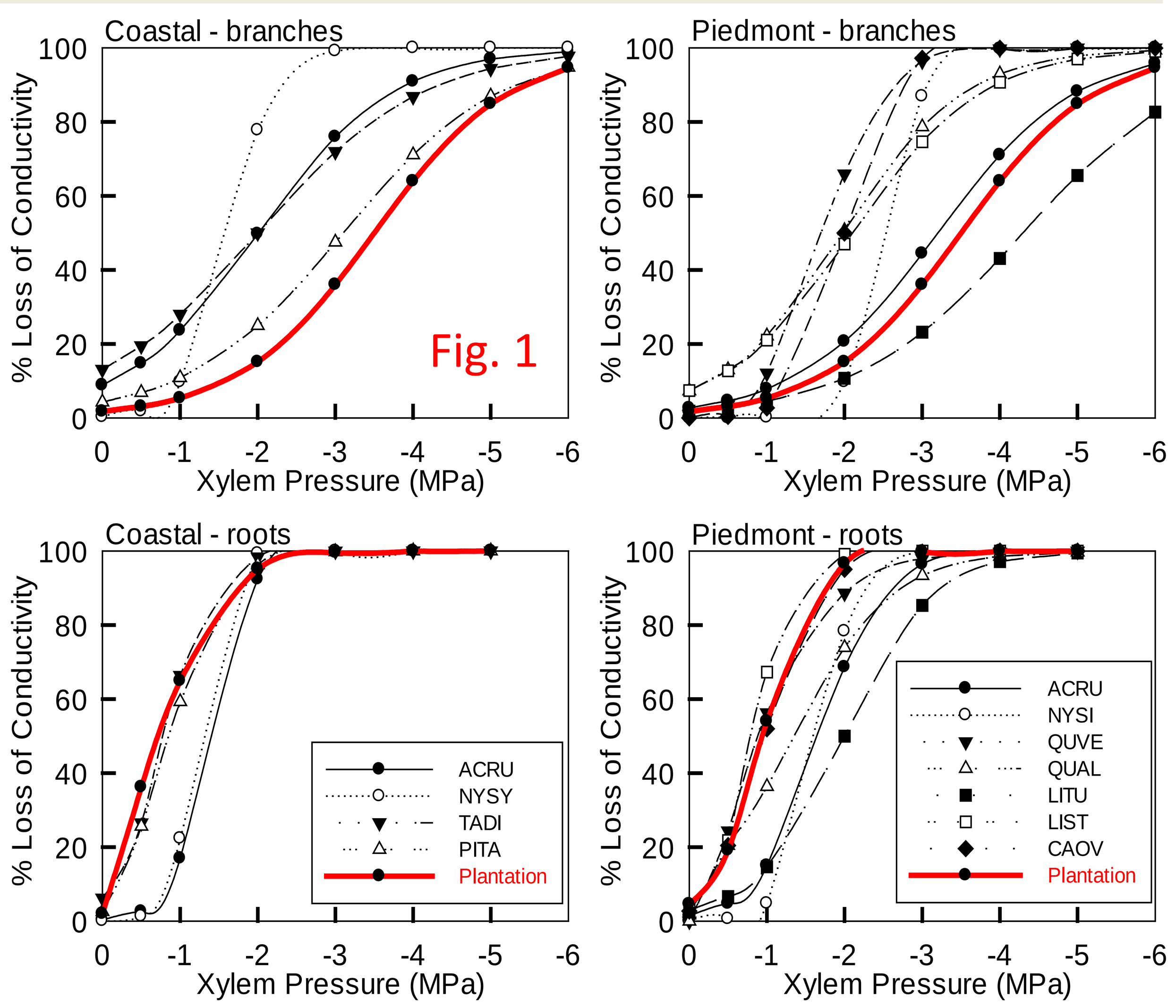
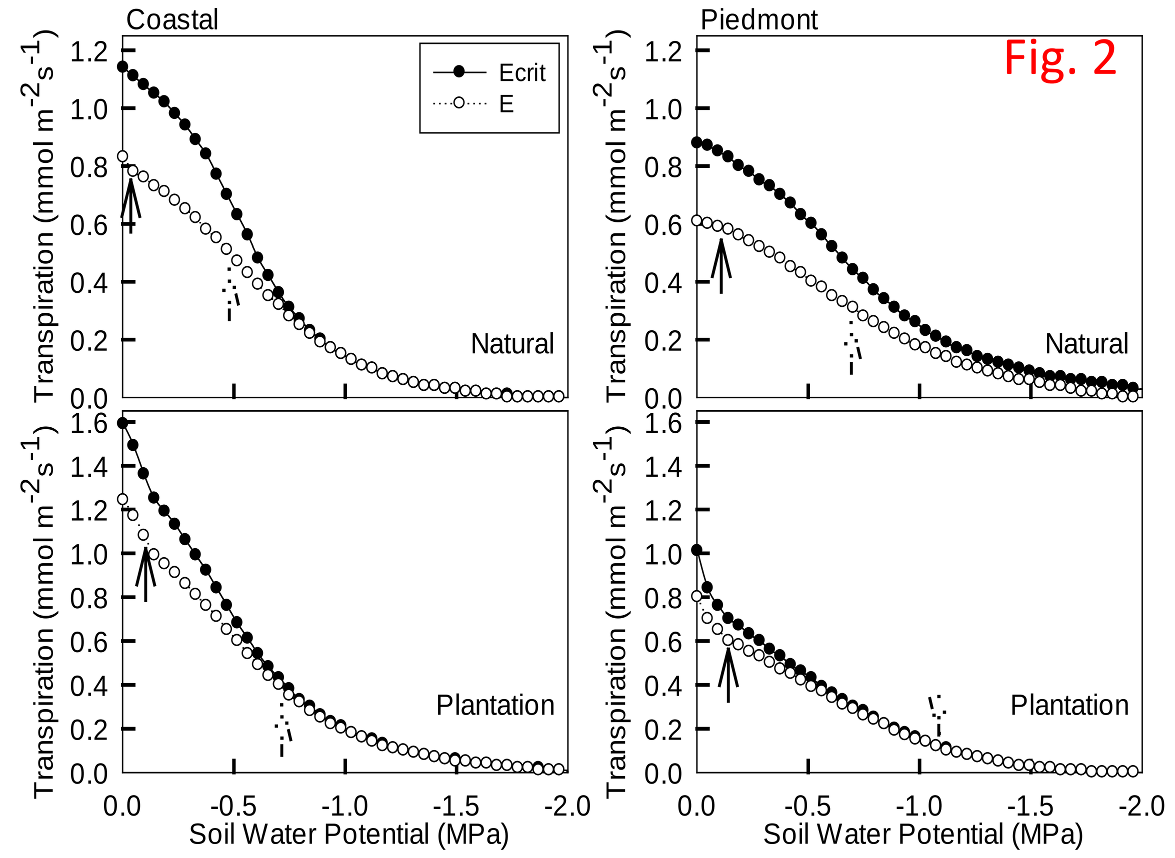


Figure 1. Resistance to cavitation of intensively managed pine plantations relative to natural hardwood species

Figure 2: Transpiration rates at full canopy vs. the integrated soil water potentials of the whole rooting zone of a natural forest or a pine plantation. **Filled and dashed arrows represent 20% and 5% Relative Extractable Water (REW), respectively.**

The critical transpiration rate (E_{crit}), which represents the maximum rate at which transpiration (E) begins to decline to prevent irreversible hydraulic failure, was higher in pine plantations than in natural forests (Fig. 2).

However, even with this higher E_{crit}, the pine plantations operated with a smaller safety margin from total hydraulic failure, especially at low soil moisture (5% REW, dashed arrows in Fig. 2).



Study sites – *P. taeda grows* on a wide range of conditions in North Carolina most of the time outside its 19th Century range. Each red dot represents a plantation stand over 5 ha.

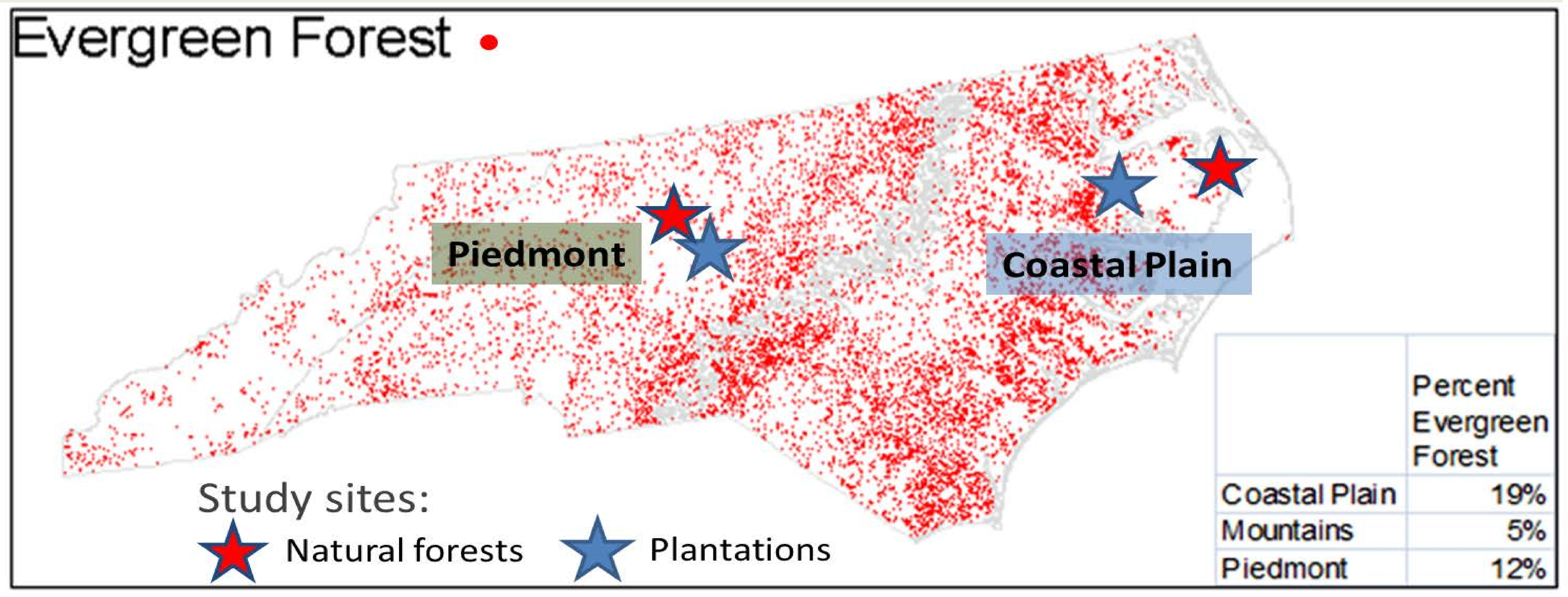


Table 1: Stand characteristics for the Coastal and Piedmont sites, which are all located in North Carolina as well as key parameter values for the hydraulic model (Sperry et al. 1998; PCE). Soil characteristics are given for the first 50 cm of soil. Root and branch P_{50} indicates the water potential at which 50% of the root or branch conductance is lost due to cavitation. $G_{s\text{-}ref}$ represents the stomatal conductance at a vapor pressure deficit (VPD) of 1 kPa (Oren et al. 1999; PCE).

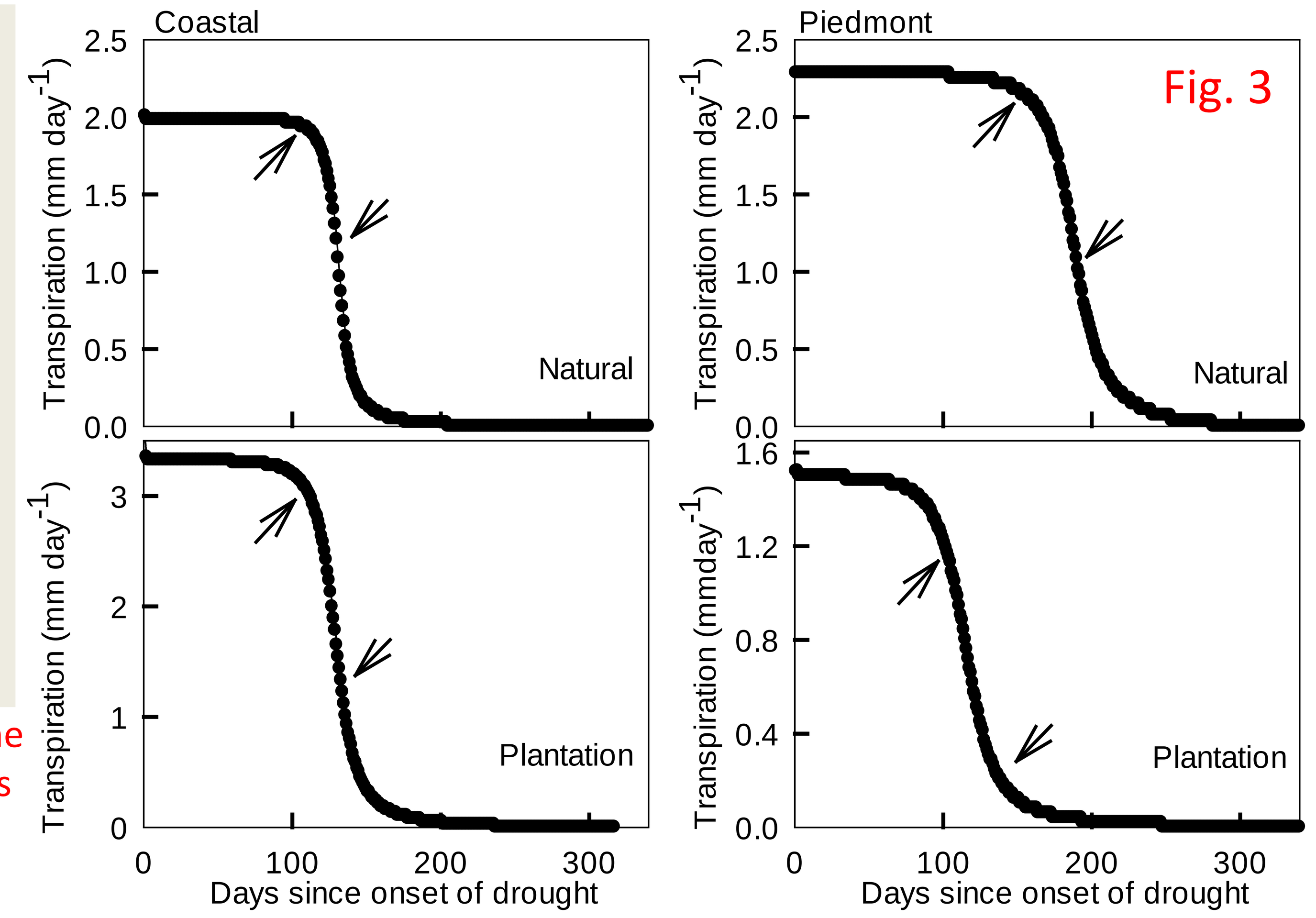
	Coastal		Piedmont	
Ameriflux database =	Natural US-AR	Plantation US-NC2	Natural US-Duke2	Plantation US-Duke1
Precipitations (mm yr^{-1}, 1945-2010)	1380	1290	1145	1145
Tree density (tree ha^{-1})	3949	645	850	1013
Stand age (years)	90-145	18	85-105	26
Tree height (m)	29-36	17-19	25-35	19-21
Leaf area index (projected)	0.9-4.0	3.0-4.4	0.3-6.0	2.0-3.5
All-sided fine root area to effective leaf area index (RAI/LAI)	3.8	1.6	2.7	1.3
Rooting depth (cm)	50	185	150	70
Sand (%) / Clay (%)	49 / 8	64 / 5.5	47 / 14.5	55 /13
Soil bulk density (g cm^{-3})	0.6	0.95	1.17	1.21
Saturated soil hydraulic conductance (K_{soil}, mol s^{-1} m^{-1} MPa^{-1})	751-856	396-436	33-42	16-24
Saturated soil water content (θ_s, m^3 m^{-3})	0.59	0.52	0.55	0.53
Saturated K_{tree} (mmol m^{-2} s^{-1} MPa^{-1})	0.31-0.84	0.87	0.36-1.36	0.75
Root P_{50} (-MPa)	0.2-0.75	0.85	0.5-1.0	1.1
Branch P_{50} (-MPa)	1.9-3.7	4.1	2.5-4.8	4.5
Reference stomatal conductance ($G_{s\text{-}ref}$, mmol m^{-2} s^{-1})	30-85	63	22-115	54
G_s sensitivity to VPD (mmol m^{-2} s^{-1} lnkPa^{-1})	10-62	35	15-80	36

Note that although LAI represents projected leaf area index, RAI/LAI, K_{tree} and $G_{s\text{-}ref}$ are expressed on an all sided-leaf-area for the plantations reflecting the fact that loblolly pine needles have stomata on all surfaces.

Our modelling outputs suggested that at the coastal sites, maximum transpiration (E) could be maintained for 60-80 days without any rain events, and that it would take about 100-105 days to deplete the soil water storage enough to reach 20% REW, and to start having a negative impacts on E (Up arrows in Fig. 3).

At the Piedmont site, for the plantation, it would take only **50 days** to the start of a decline in transpiration.

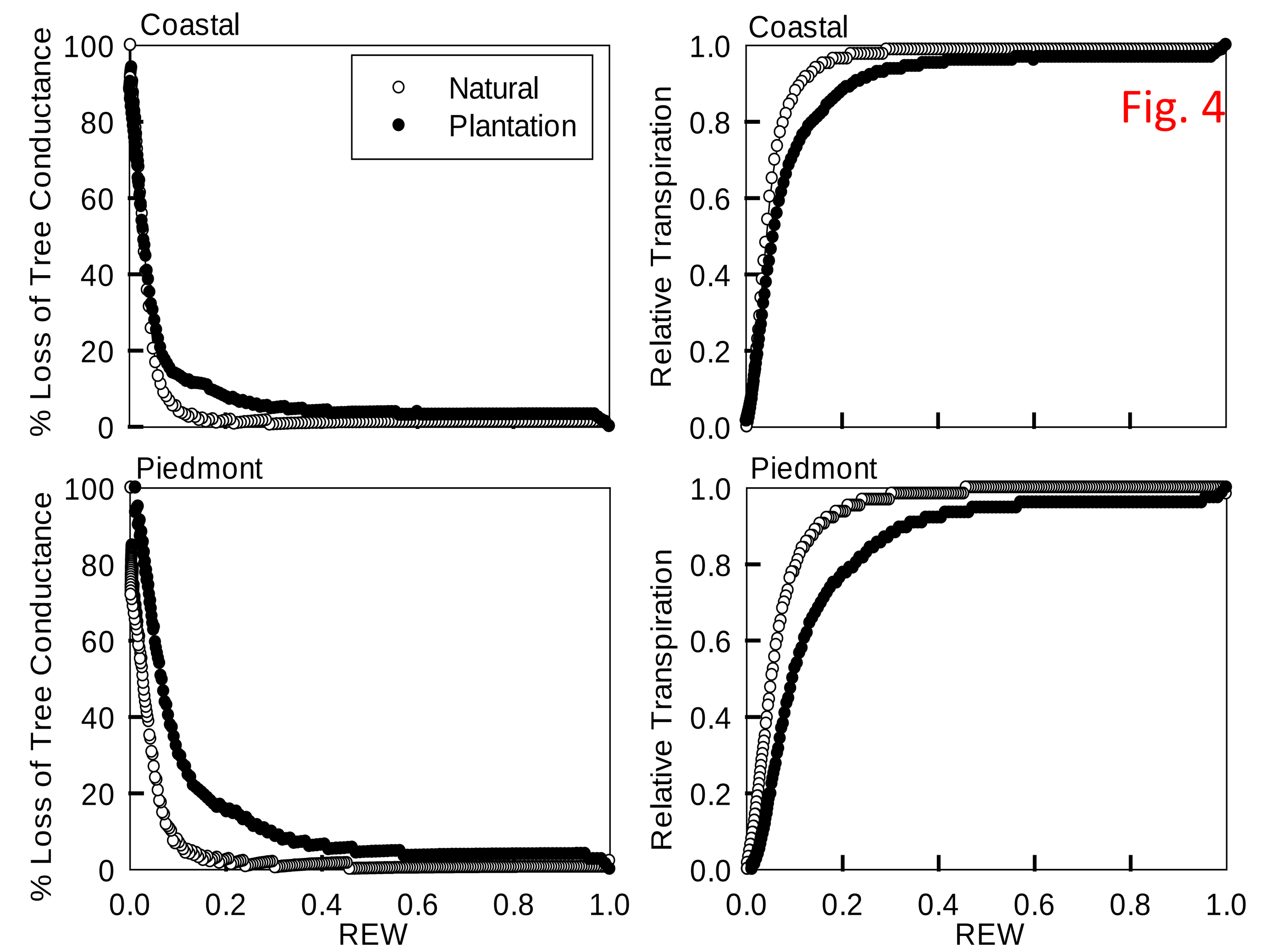
Figure 3: Daily transpiration rates vs. the number of days without any rain events in a natural forest or a pine plantation **(Up and Down arrows represent 20% and 5% soil REW, respectively).**



There was a sharp decrease in transpiration and tree hydraulic conductance below 20% relative extractable water (REW) for both plantations, and below 10% REW for the natural stands (Fig. 4).

Consequently, at the onset of drought (REW = 20%), transpiration was predicted to decrease by less than 10% in both natural stands and by more than 20% in plantations.

Figure 4. Whole-tree loss of hydraulic conductance (left panels) and relative transpiration (right panels) at the full canopy stage versus soil REW.



Highlights – Conclusions (see Domec et al. 2015 For. Ecol. Management)

- ❖ A water transport model fitted with stand-specific hydraulic parameters (Table 1, Fig. 1). was used to predict the resilience of natural vs planted forests to extreme drought.
- ❖ Trees from natural hardwood forests had roots less vulnerable to cavitation compared to the pine plantations (Fig. 1).
- ❖ Trees from natural forests had larger root to leaf area ratio compared to the planted pines (Table 1).
- ❖ Plantations operated at xylem tensions capable of inducing hydraulic dysfunction (Fig. 2).
- ❖ Plantations are more susceptible to drought compared to natural forests (Fig. 3, Fig. 4).

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ABSTRACT

Throughout the southern US, past forest management practices have replaced large areas of native forests with loblolly pine plantations and have resulted in changes in forest response to extreme weather conditions. However, uncertainty remains about the response of planted versus natural species to drought across the geographical range of these forests. Taking advantage of a cluster of unmanaged stands (85–130 year-old hardwoods) and managed plantations (17–20 year-old loblolly pine) in coastal and Piedmont areas of North Carolina, tree water use, cavitation resistance, whole-tree hydraulic (K_{tree}) and stomatal (G_s) conductances were measured in four sites covering representative forests growing in the region. We also used a hydraulic model to predict the resilience of those sites to extreme soil drying. Our objectives were to determine: (1) if K_{tree} and stomatal regulation in response to atmospheric and soil droughts differ between species and sites; (2) how ecosystem type, through tree water use, resistance to cavitation and rooting profiles, affects the water uptake limit that can be reached under drought; and (3) the influence of stand species composition on critical transpiration that sets a functional water uptake limit under drought conditions. The results show that across sites, water stress affected the coordination between K_{tree} and G_s. As soil water content dropped below 20% relative extractable water, K_{tree} declined faster and thus explained the decrease in G_s and in its sensitivity to vapor pressure deficit. Compared to branches, the capability of roots to resist high xylem tension has a great impact on tree-level water use and ultimately had important implications for pine plantations resistance to future summer droughts. Model simulations revealed that the decline in K_{tree} due to xylem cavitation aggravated the effects of soil drying on tree transpiration. The critical transpiration rate (E_{crit}), which corresponds to the maximum rate at which transpiration begins to level off to prevent irreversible hydraulic failure, was higher in managed forest plantations than in their unmanaged counterparts. However, even with this higher E_{crit}, the pine plantations operated very close to their critical leaf water potentials (i.e. to their permissible water potentials without total hydraulic failure), suggesting that intensively managed plantations are more drought-sensitive and can withstand less severe drought than natural forests.

1. Introduction

In the southern US, the most common land conversion by area was from native mixed hardwood forests to pine plantations. It is estimated that more than 10 million ha of forests were harvested or cleared between 1973 and 2000 (Drummond and Loveland, 2010). Additionally, wetlands cover around 8% percent of the 20 eastern US ecoregions and plantations caused a loss of more than 500,000 ha of wetland since 1980, including a large proportion of forested wetland (Loveland et al., 2002). In the Southern Coastal and the Middle Atlantic Coastal Plains alone, 2.4–5.0% loss of wetlands occurred during the past 25 years (Daniel and Dahlen, 2002;

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