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Research paper

Woody bioenergy crop selection can have large effects on water yield: A southeastern United States case study

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ABSTRACT

Short-rotation woody crops in the southeastern United States will make a significant contribution to the growing renewable energy supply over the 21st century; however, there are few studies that investigate how species selection may affect water yield. Here we assessed the impact of species selection on annual and seasonal water budgets in unvegetated plots and late-rotation 14–15-year-old intensively managed loblolly pine (*Pinus taeda* L.) and sweetgum (*Liquidambar styraciflua* L.) stands in South Carolina USA. We found that while annual above-ground net primary productivity and bioenergy produced was similar between species, sweetgum transpiration was 53% higher than loblolly pine annually and 92% greater during the growing season. Canopy interception was 10.5% of annual precipitation and was not significantly different between the two species. Soil evaporation was less than 1.3% of annual precipitation and did not differ between species, but was 26% of precipitation in unvegetated plots. Annual water yield was 69% lower for sweetgum than loblolly pine, with water yield to precipitation ratios of 0.13 and 0.39 for sweetgum and loblolly pine, respectively. If planted at a large scale, the high transpiration and low water yield in sweetgum could result in declines in downstream water availability relative to loblolly pine by the end of the growing season when storage in groundwater, streams, and water supply reservoirs are typically at their lowest. Our results suggest that species selection is of critical importance when establishing forest plantations for woody bioenergy production due to potential impacts on downstream water yield.

1. Introduction

Renewable energy sources such as solar, wind, and bioenergy are projected to increase by 2.6% annually between now and 2040 [1]. The European Union (EU) 2020 Climate and Energy Package put into legislation in 2009 a target of 20% of EU energy from renewables by 2020. Biomass from forest and agricultural products will necessarily comprise a large share of the energy to achieve this goal [2]. However, the EU will need to import biomass from other nations due to a limited local supply and North America will be a potential source of forest and agricultural biomass to meet this demand [3]. Regardless of where biomass production occurs, increases in global demand will put additional pressure on forests and agricultural lands. For example, total potential biomass from forest and agricultural products in the United States for bioenergy production is predicted to increase nearly 250% between 2017 and 2040 [3]. This increase is driven primarily by increases in potential biomass from agricultural sources including crop residues, herbaceous crops (e.g., switchgrass, miscanthus, biomass sorghum, and energy cane), and short-rotation woody crops. While potential biomass available from forests (logging residues and whole tree biomass) is projected to remain relatively stable over the coming decades (approximately 86 million dry tons), potential biomass from short-rotation woody crops is predicted to increase from three to seven million dry tons from 2022 to 2040.

Forests in the southeastern United States have great promise for providing woody biomass for energy production, but additional demand placed on forest ecosystems could have negative impacts on other ecosystem services. Across the 13 southern states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia), there are

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99 million ha of forest covering 46% of the total land area [4]. At the end of the 20th century, these southern forests accounted for 60% of the nation's timber products [5] and provided 31 billion kg of dry forest residue alone (not including purpose-grown woody bioenergy crops), or 55% of the total United States forest residue production [6]. Over 80% of forest biomass originates on privately owned forest land in the United States [3] and 87% of forested land in the southeastern United States is privately owned [4]; thus, private landowners in the region will be making individual management decisions to balance biomass production and profit with other forest ecosystem services.

While there is ample supply of woody biomass in the region, there has been growing concern about how increasing bioenergy production in the southeastern United States may impact the environmental resources [2,7,8]. Among the potential impacts, intensively managed woody crops may use more water than the land uses they replace depending on species selection [9]. Water is historically abundant in the Southeast, but climate change and increased frequency and severity of drought will limit water supply [10]. In addition, changes in forest land cover, species composition, and management will have an impact on water availability to humans and aquatic ecosystems [11–13]. From a water resource perspective, we will need to understand species-specific water use rates and impacts on water yield (i.e., the excess water that contributes to streamflow, groundwater recharge, or soil water storage) and downstream water availability [14].

Evapotranspiration is affected by the tree species that comprise a forest ecosystem [15,16]. For example, growing season daily transpiration rates among southern Appalachian forest canopy species (adjusted for differences in tree size) can vary by more than four-fold, and co-occurring species can differ considerably in their responsiveness to climatic variation [15,17,18]. Species specific leaf habit and phenology (evergreen vs. deciduous) can impact the magnitude and seasonality of evapotranspiration [19,20], as can functional rooting depth [21–23], sapwood area [24], as well as xylem anatomy [15,16] and related leaf water potential regulation strategy (i.e., iso-vs. anisohydric) [25]. Other components of evapotranspiration that can be influenced by species composition include soil evaporation and interception/evaporation of precipitation by the canopy and forest floor. Interception and evaporation can together be 10–15% of annual precipitation *P* [15,26] and are affected by canopy closure and uniformity, bark characteristics, and leaf shape and inclination [27].

While information on relative productivity and water use among species exists, data describing the complete water budgets and energy production for managed mono-culture stands of different species commonly used as bioenergy crops under similar site conditions are lacking. King et al. [9] provided a thorough review of 371 water use studies and concluded that "the data needed to design water-efficient bioenergy cropping systems are currently not available" and that "a widespread network of research sites encompassing the major climatic zones and soils needs to be installed with an eye toward quantifying a site's water balance as a function of climate variation." Chiu and Wu [14] further suggested that in addition to climatic zones and soils, the choice of feedstock mix (i.e., species selection) is a factor that must be considered when assessing the impact of bioenergy production on water resources. There continues to be a need for field-based studies providing detailed knowledge of the ecophysiology and water relations of the major bioenergy crops [9].

Loblolly pine (*Pinus taeda* L.) and sweetgum (*Liquidambar styraciflua* L.) have potential as short-rotation woody bioenergy crops in the southeastern United States; however, very little is known about how species selection may affect water yield from forested catchments in the region. Forestry practitioners agree that loblolly pine (LP) is the primary candidate for bioenergy production and the benchmark from which to compare productivity of other potential woody crop species in the southeastern United States [28]. Sweetgum (SG) is currently considered the best hardwood option for most of the Southeastern region as it tolerates a range of site conditions [29,30] and demonstrates fairly consistent production rates [28]. Previous studies suggest somewhat greater productivity for LP relative to SG [9,31], although relative differences between species depend on site conditions and resource availability.

Differences in the anatomy and physiology between LP and SG may result in differences in water use. For example, LP has a tracheid xylem anatomy consisting of relatively smaller diameter water conduits and a tortuous flow-path while SG xylem has a diffuse-porous xylem anatomy with well-connected flow-paths and relatively larger vessels for transporting water [32]. SG and LP transpiration also differs in response to atmospheric conditions such as vapor pressure deficit and photosynthetically active radiation [33,34]. A more conductive xylem anatomy associated with SG would suggest higher transpiration rates than LP during the growing season; however, the effects of these characteristics on transpiration and water yield have not been quantified in monoculture even-age stands (i.e., short-rotation woody bioenergy crops).

The objective of this study was to characterize and compare the annual and seasonal water budgets in relation to biomass and energy production for late rotation 14–15-year-old, intensively managed LP and SG stands in South Carolina USA. We hypothesized that 1) LP would use more water during the dormant season due to year-round transpiration and interception of this evergreen species, but that SG would use more water during the growing season due to differences in physiology, 2) the net effect of differences in seasonal water use will result in a negligible difference in annual water use and water yield, and 3) LP and SG will have similar water use efficiency (WUE: carbon gained per unit water consumed) and bioenergy WUE (WUE_b: energy produced per unit water consumed) due to similar annual water use rates and similar rates of productivity. In addition to LP and SG stands, we quantified the water budget of unvegetated bare (BA) plots to isolate the vegetation effects and to provide a basis of comparison for the 14-15 year-old stands relative to conditions at the time of planting. Our goal was to assess the overall potential impact of managed stands for bioenergy production on water yield, and how species selection may impact water availability on annual and seasonal time scales.

2. Methods

2.1. Site description

The US Department of Energy's Savannah River Site is a national environmental research park located near Aiken, SC, USA in the Carolina Sandhills ecoregion (Fig. 1). The climate is humid continental with warm summers and mild winters [35]. Average annual temperature and precipitation for Aiken, SC between 1981 and 2010 was 17.5 °C and 1299 mm, respectively (www.dnr.sc.gov/climate/sco/ClimateData/8110Normals.php). Average minimum temperature in January is 0.4 °C; average maximum temperature in July is 33.5 °C. The Savannah River Site spans the Aiken plateau of the Sandhills physiographic region and the Pleistocene coastal terrace of the Upper Coastal Plain. Soils are predominately in the Blanton series (Loamy, siliceous, semiactive, thermic Grossarenic Paleudults) consisting of very deep, somewhat excessively drained to moderately well drained fine sands [36].

Our study utilized established forest plots from an existing short-rotation woody crop productivity project. The site, plant materials, and experimental design have been previously described in greater detail [37], and a number of previous publications describe stand responses to irrigation and fertilizer treatments [31] and disturbances [38], as well as general physiological [39] and ecological processes [40]. Briefly, loblolly pine (*Pinus taeda* L.), sweetgum (*Liquidambar styraciflua* L.), American sycamore (*Platanus occidentalis* L.), and eastern cottonwood (*Populus deltoides* Bartr.) seedlings were planted in 0.2 ha plots (52.5 m × 42 m) at a 2.5 m × 3.0 m spacing in February 2000. We selected three replicate plots each of sweetgum (SG) and loblolly pine