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Research paper

Water quantity implications of regional-scale switchgrass production in the southeastern U.S.

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ABSTRACT

Expansion of ethanol production has led to regional-scale cultivation of cellulosic biofuel crops, such as switchgrass (*Panicum virgatum* L.), on agriculturally marginal lands. A range of forest-based solutions are also being evaluated, especially in the southeastern U.S. However, there may be unanticipated environmental consequences, including changes in water export when managing forests to accommodate biofuel demands at a regional scale. We used the Soil Water Assessment Tool (SWAT) to simulate effects of regional-scale conversion of loblolly pine (*Pinus taeda* L.) plantations to switchgrass biofuel production on stream flow in the ~5 million ha Tombigbee River Watershed in the southeastern U.S. Greater than 50% of the Tombigbee Watershed is forested, with 20% of the watershed supporting primarily loblolly pine forests. We modified the SWAT model by adding five age classes of loblolly pine trees, to more accurately represent existing forested systems. We found that maximum conversion of loblolly pine to switchgrass, affecting 7% of the watershed, represented an extreme land-use change and resulted in a 4% increase in annual stream flow. The more operationally and economically feasible option of converting young (≤4 yrs) and old (≥16 yrs) loblolly pine stands to switchgrass on <8% slope (2% of the watershed) resulted in a 2% increase in stream flow. Changes in annual stream flow were driven primarily by alterations in evapotranspiration (ET). Seasonal changes in stream flow were attributed to complex interactions among water-balance components of ET, surface flow, and groundwater flow.

1. Introduction

Fluctuations in oil prices and strong interest in achieving energy independence have led to a dramatic expansion in ethanol production and alteration of the agricultural landscape [1,2]. Currently, in the U.S., ethanol biofuel production is predominately from the fermented sugars in corn (*Zea mays* L.); of the approximately 50.3 billion liters of ethanol produced in the U.S. in 2012, >95% came from corn starch [3]. However, competition of feed and food demands on grain supplies will eventually limit expansion of corn ethanol capacity [4,5]. Energy production from cellulose-based biomass (such as corn stalks and wheat straw, native grasses, trees, and forest residues), rather than from sugar-based materials, can provide an alternative non-food, non-feed-based feedstock [3]. Early studies indicate warm-season C4 perennial grasses such as switchgrass (*Panicum virgatum* L.) retain soil and nutrients in place, require lower fertilizer inputs, and are efficient water users, thus reducing water quality and quantity impacts often associated with corn production [6–11].

Demand for dedicated energy crops is expected to grow with development of bioenergy markets [12], resulting in significant alterations to current land-use [13]. Large-scale cultivation of cellulosic biofuel crops, such as switchgrass, on agriculturally marginal land or surplus lands using standard agricultural practices is one option being considered to meet biofuel demand [14]. Intensively managed forested lands could also be converted to agro-forestry systems for biofuel production [15]. Production of switchgrass from forested systems could diversify economic returns for land-owners while maintaining soil quality and biodiversity without significant diversion of agricultural crops from food production [16].

The southeastern and Gulf Coast regions of the U.S. have >15 million ha of pine (*Pinus* spp.) plantations [17] and some of the most

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rapid population growth in the country, along with increasing pressure to develop these forested lands [17,18] to accommodate cellulosic biofuel demands [19]. This region of the U.S. could be a vital source of cellulosic biofuel because of its long growing season, favorable temperature, sufficient water, and suitable soil [20]. However, expansion of biofuel production may cause unintended environmental consequences that are not yet understood [13,21–24], especially at large regional scales [25–27].

One of the primary concerns with switchgrass is its potential to increase water export from watersheds [28,29]. The few studies that have looked at conversion of pine forests to grasslands observed higher annual stream flow (e.g., [30,31]), attributed to reductions in evapotranspiration (ET) and interception by vegetation, increased storm flow, and increased baseflow via increased groundwater recharge [30–32]. To date, there are no reports directly assessing impacts on stream flow of large-scale switchgrass production replacing pine forests. Given the expected differences in stream flow from pine forests versus switchgrass plantations, it is important to consider potential changes in regional water output that are likely to occur if hundreds of thousands of hectares of land are converted to switchgrass production, especially given the potential for associated environmental responses such as water-quality degradation that are often integrally linked with stream flow changes [25,26,28].

Field experiments using paired watersheds are commonly used to assess effects of changes in land use on stream flow, but are limited to smaller basins where applying land-use treatments on a watershed scale are possible. In single-watershed experiments, effect of land-use change on water resources is assessed by measuring conditions before and after the change in land use. In these experiments, it is more difficult to separate effect of land-use change from effects of changes in weather and climate patterns. Regional field-scale measurements to examine large-scale effects of vegetation land-use change on water resources are cost-prohibitive and, in most cases, it is also difficult to control experimental boundary conditions and to measure precipitation and stream flow accurately at these larger spatial scales.

In recent years watershed-scale hydrologic models have frequently been used to simulate effects of land-use change and management scenarios at a range of spatial scales [25,26,33–37]. The Soil and Water Assessment Tool (SWAT) can model effect of regional-scale switchgrass production on water resources, but has several limitations that make it difficult to apply to land-use change involving forests, as SWAT assumes all trees on the landscape are even-aged and mature.

To examine potential effects of large-scale conversion of forests for biomass production of a perennial herbaceous crop, we evaluated regional-scale impacts to stream flow of converting existing pine forests to a switchgrass bioenergy cropping system under a gradient of conversion scenarios. In a unique collaboration with Weyerhaeuser Company, who are assessing potential impacts of large-scale conversion of loblolly pine (*Pinus taeda* L.) forests to biofuel production in the southeastern U.S., we modified the SWAT model by inserting loblolly pine stands of varying age classes in the five-million-ha Tombigbee Watershed of the southeastern U.S. (Fig. 1), where large-scale commercial loblolly pine plantations currently exist and where switchgrass production is feasible.

We used the model to predict effects on stream flow of three land-use-change scenarios recommended by Weyerhaeuser, ranging from maximum conversion of pine plantations to switchgrass to a more operationally and economically realistic and modest conversion of pine plantations to switchgrass. We predicted that changes in seasonal and annual stream flow, compared to the baseline model using existing land-use categories, would be highest with the maximum conversion and least with more conservative conversion invoking more operational limitations. We hypothesized that changes in stream flow among the conversion scenarios would be controlled primarily by differences in the ET component of the water balance equation for the Tombigbee Watershed in Alabama and Mississippi, U.S.

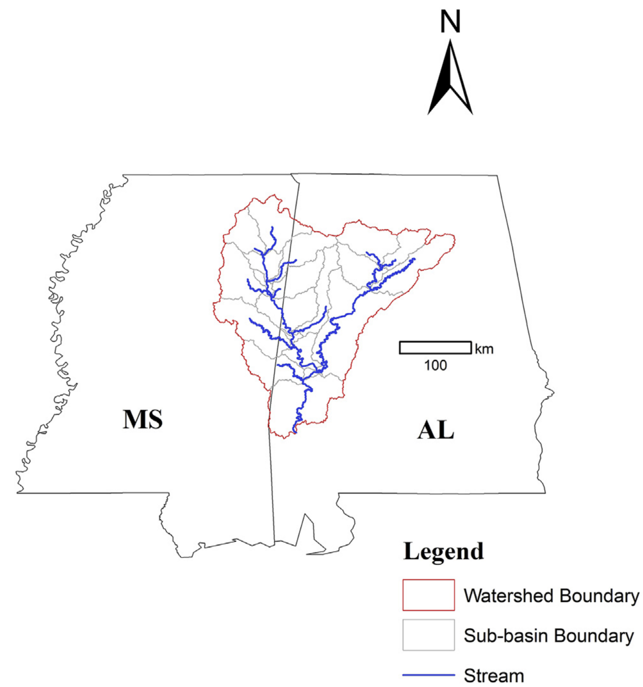

Fig. 1. The Tombigbee Watershed encompasses approximately five million ha and is a major subwatershed of the Mobile River Basin, draining portions of Mississippi (MS) and Alabama (AL), U.S. Approximately 53% of the watershed is forested, 23% is agricultural, 6% is urban, and 12% contains other land-use categories.

2. Materials and methods

2.1. Study watershed

The Tombigbee Watershed encompasses approximately five million ha and is a major subwatershed of the Mobile River Basin, draining portions of Mississippi and Alabama (Fig. 1). Cities within the Tombigbee Watershed with populations of ≥100,000 include Birmingham and Tuscaloosa, Alabama. Approximately 53% of the watershed is forested, 23% is agricultural, 6% is urban, and 12% contains other land-use categories. Rural land-use activities include row crops such as cotton, corn, and soybeans; aquaculture; poultry and cattle production; and silviculture. Major industries in the basin include power production; and chemical, pulp, paper, iron, steel, coal, and textile production [38].

The major physiographic province in the Tombigbee Watershed is Coastal Plain with some Piedmont and Valley and Ridge physiographic provinces located in the northeastern corner of the watershed [38]. Piedmont is generally characterized by igneous and metamorphic rocks, whereas Valley and Ridge consists of a series of parallel ridges and valleys, all having a northeast orientation and underlain by sandstone, shale, limestone, and dolomite rocks. The Coastal Plain is primarily underlain by unconsolidated or poorly consolidated sands, gravels, clays, and limestone. Elevation in the study unit ranges from 76 to 231 m and mean annual precipitation is 1397 mm (2001–2008) [38]. Mean annual stream flow of the Tombigbee River Basin is 866 m^3/s (2001–2008) [39]. The principal tributary to the Tombigbee River is the Black Warrior River Basin