Title: Simulated Longleaf Pine (*Pinus palustris* Mill.) Restoration Increased Streamflow -- a Case Study in the Lower Flint River Basin

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Abstract:

Water scarcity in the southeastern United States has increased in recent decades due to population growth, land use intensification, and climate variability. Precipitation is relatively abundant, but declines in streamflow suggest a need to better manage water yield. Restoration of low-density, frequent-fire longleaf pine (*Pinus palustris* Mill.) woodlands, which once dominated the southeastern Coastal Plain, represents a possible strategy to increase water yield and mitigate water scarcity. The Flint River Basin has seen recent conflicts over water appropriations and lies within the historic range of longleaf pine. We used the Soil and Water Assessment Tool (SWAT) to evaluate the potential effect of longleaf pine restoration on streamflow in the Ichawaynochaway Creek, a major tributary of the Flint River. Parameters governing plant water use, e.g. leaf area and leaf physiology, were adjusted to create a longleaf pine land cover. We simulated the conversion of ~95,000 ha of existing forest to longleaf pine, an increase from 3% to 35% of landcover in the basin. Modeled evapotranspiration was lower for longleaf pine compared to other forest types in the region, and conversion to longleaf pine increased annual water yield by 17.9 ± 1.6 mm, or 5.2%. Proportional changes in monthly streamflow were up to 74% higher during low flow periods, when in-stream habitat is most vulnerable. Restoration of longleaf pine could be a promising way to mitigate water scarcity in the southeastern U.S., and adding flow during extreme droughts may prove vitally important for conserving imperiled aquatic organisms.

1 Introduction

Incidents of water scarcity are becoming a regular occurrence in the southeastern United States, with consequences for both human water supply and aquatic ecosystems. Recent severe droughts (Palmer drought severity index <-4, 2007, 2011, and 2012, NOAA), coupled with increasing water demands from the agricultural, municipal, and forestry sectors are stressing economic and political systems not usually accustomed to water scarcity (Ruhl, 2005; *Florida v. Georgia*, 2021). The region is also projected to experience temperature rise >1.5°C (IPCC, 2013) and a 10–30% increase in consecutive dry days by 2100 (Melillo et al. 2014). The combination of temperature rise, population growth, and expansion and intensification of the agricultural and forest economy will lead to even greater water demands. Simultaneously, forest losses to urban land cover and changes in forest management, coupled with shifts in precipitation patterns will cause more uncertainty in water supply (Emanuel & Rogers, 2012; Weir & Greis, 2013; Golladay et al., 2016). Demands on forest resources from a growing population, including wood and non-traditional forest products, recreational opportunities, and other ecosystem services like provision and regulation of water supplies, are expected to increase. These trends require creative conservation solutions that result in multiple benefits to optimize conservation investments.

Perhaps nowhere are these trends more apparent than in the Apalachicola-Chattahoochee-Flint (ACF) River watershed. The basin covers parts of Alabama, Georgia, and Florida; and drains into the Gulf of Mexico at Apalachicola Bay. The northern half of the basin in most heavily impacted by municipal withdrawals in and around Atlanta, GA. The southern half of the basin, especially the Lower Flint River Basin (LFRB) has some of Georgia's most productive agricultural land. Agricultural water consumption increased substantially in the 1970s with the introduction of center-pivot irrigation (Pierce et al., 1984; Couch et al., 1996). High agricultural water demands in the region are met with a combination of surface water from creeks and groundwater from the Upper Floridan Aquifer (Hook et al., 2005). Total water withdrawals in the lower basin are ~3.25 billion liters per day (2017 Flint-Ochlockonee Regional Water Plan), with most of this water consumed by crop evapotranspiration after application. This level of water consumption and recent droughts have resulted in increased vulnerability of aquatic ecosystems to drying. In the lower Flint, streamflows are declining during the peak growing season, particularly during seasonal or climatological dry and drought periods (Rugel et al., 2012; Emanuel & Rogers, 2012). Streams that were once perennial are becoming intermittent and once intermittent streams are experiencing longer and more extreme dry periods (Gordon et al., 2012). Throughout the basin, recent streamflow declines during dry periods greatly exceed those during similar periods in the historic record (Golladay et al., 2007; Rugel et al., 2012). Reduced summer streamflow and increased stream temperature have implications for ecological communities in the river. Freshwater mussels, a group of concern in the

Flint River, have experienced declines in abundance associated with dry and drought flows (Golladay et al., 2004). Fish communities have also been impacted due to altered flows and water quality changes (Davis et al., 2020).

Because row crop agriculture is one of the largest land cover types and the largest single consumer of water in the region, many efforts have focused on reducing agricultural water use. Recent innovations in irrigation technology have improved the efficiency of water application to cropped areas (2017 Lower Flint Ochlockonee Regional Water Plan). However, during dry or drought periods water demand is still great, and stress on water resources is ongoing. Modern irrigation equipment such as low-pressure drop nozzles have improved irrigation efficiency, and new technologies such as variable rate irrigation and smart irrigation scheduling are being developed and implemented to reduce agricultural water use (Vellidis et al., 2016a-c; Masters 2019). However, these water-saving technologies are reaching the limits of their potential to reducing water consumption while maintaining economically valuable commodities, suggesting the need for other solutions.

While agriculture has had significant impacts on watershed function, it must be noted that less than 30% of land cover in the LFRB is irrigated row crop (Homer et al., 2015). Thus, managing rural watersheds for improved water yield will require novel approaches that leverage the full portfolio of land cover types. Approximately half of the LFRB is forested, and the entire basin falls within the historical range of longleaf pine woodlands. Longleaf pine (*Pinus palustris* Mill.) woodlands, often referred to as longleaf savannas, historically dominated the coastal plain of the southeastern United States, covering >90 million acres (Frost, 2007). Overharvest, land conversion to other pine species and non-forest land, and decades of fire exclusion contributed to ~95% of loss of longleaf pine across its range with remaining stands highly fragmented (Noss et al., 1995; Outcalt & Sheffield, 1996; Kirkman et al., 2017). Longleaf pine woodlands are noted for high biodiversity and serve as critical habitat for endemic species making conservation and restoration a high priority for many stakeholders in the southeast. While restoration and conservation of longleaf pine to date has focused on wildlife and species richness, the unique structure and function of longleaf pine woodlands may promote other ecosystem services, including high water yield (McLaughlin et al., 2013; Brantley et al., 2017).

Restoring longleaf pine ecosystem can potentially benefit water yield by reducing whole-watershed evapotranspiration (ET), especially during drought (McLaughlin et al., 2013; Brantley et al., 2017). At the individual plant scale, longleaf pine has been shown to demonstrate higher stomatal sensitivity to soil moisture, resulting in 33% lower daily transpiration when compared to slash pine (*Pinus elliottii*) (Gonzalez-Benecke et al., 2011). At the stand level, the structure of frequently burned longleaf pine woodlands is often low density, which translates into low basal area and low leaf area. Frequent fire also suppresses hardwood competition and promotes herbaceous groundcover development (Fill et al., 2015; Kirkman & Giencke, 2017). Wiregrass (*Aristida stricta*), a major groundcover species in much of the longleaf pine range, depends on fire for flowering and fertile seed production (Outcalt, 1994). Utilizing the C4 metabolic pathway, wiregrass demonstrates high water-use efficiency when compared to many woody species common in the region (Ford et al., 2008; Brantley et al., 2017). Stand level ET of longleaf pine has been reported as low as 489 mm/year (Ford et al., 2008) and as high as 816 mm/year (Whelan et al., 2015), much lower than the ET of slash/loblolly pine plantations in the same region at ~950 mm/year (McLaughlin et al., 2013) and lower than many hardwood forests in the southeastern U.S. (McLaughlin et al., 2013; Brantley et al. 2017). Thus, large-scale restoration of longleaf pine woodlands with its characteristically low ET represents a promising land management strategy to improve water yield and mitigate water scarcity.

Our objective was to quantify potential stream responses of large-scale longleaf pine restoration. We used a watershed scale model to simulate conversion from other forest types to longleaf pine in the Ichawaynochaway Creek (henceforth INC), a major tributary of the lower Flint River with land use representative of the region. Like the LFRB, the INC has seen abnormally low growing season streamflows during dry periods and droughts (Rugel et al., 2012). While the watershed largely overlaps with the historic range of longleaf pine, only ~3% of total area of the watershed is currently longleaf pine woodland. Deciduous forests, mixed hardwood forests, and evergreen forests with other dominant pine species, such as loblolly pine and slash pine, make up 32% of the land area. We simulated the conversion from these forest types to low density longleaf pine woodlands similar to those found in natural, frequently burned stands. We hypothesized that longleaf pine restoration would increase annual water yield, that monthly streamflow would generally increase, and that the most pronounced streamflow effects would be during growing season low-flow periods, especially early fall. Finally, we discuss the potential importance of this additional water for in-stream habitat and aquatic ecosystem health.

2 Methods

2.1 Study Area

The study focused on the INC watershed, a 2940 km^2 HUC-8 watershed in the Gulf Coastal Plain of southwestern Georgia, USA (Fig. 1). The main stem of the creek originates near Weston, GA, USA (31.98, -84.64) and flows southward until it reaches the Flint River below Newton, GA (31.17, -84.47). The northern half of the INC flows through the Fall Line Hills physiographic district of the upper Coastal

Plain region. The southern reaches cross the Dougherty Plain physiographic district, where the creek channel interacts with groundwater from the Upper Floridan aquifer. The U.S. Geological Survey stream gages within the watershed have up to 75 years of flow records from the mid-1900's to today, a period representing significant land use change (Pierce et al., 1984; Fanning et al., 2001). Golladay & Battle (2002) and Golladay et al. (2004) provide more detailed descriptions of the creek. Climate in the study area is humid subtropical (Peel et al., 2007) with hot, humid summers and mild winters (mean annual temperature 19°C). Mean annual precipitation is ~1310 mm and is distributed fairly evenly across the year (http://www.ncdc.noaa.gov, 30-year average 1987-2016). The study period (2000– 2016) represented substantial variations in climate, including three multi-year droughts (1999-2001, 2006-2008, and 2010-2013) (Qi et al., 2020). Monthly rainfall averages about 110 mm (range 10–350 mm). Periods of above-average rainfall also were also common during the study period with monthly totals as high as 350 mm.

Land use in the INC watershed is dominated by agriculture (~50%), which is split between pasture, irrigated row crops, and some limited dryland farming. Row crop farming of mainly *Gossypium* spp. (cotton), *Arachis hypogaea* (peanuts), and *Zea mays* (corn) is irrigated by center pivot systems using groundwater sources from the Upper Floridan Aquifer and surface water from the INC, its tributaries, and adjacent multi-function ponds (Hook et al., 2005). Groundwater is the largest source for irrigation for the study region (Fanning et al., 2001). Remaining acreage is upland forest (35%), wetlands (14%) and urban area (1%) (Fig. 1) (National Land Cover Database, 2011; Homer et al., 2015). Streams have minimal urban impacts and are often buffered by forests resulting in good water quality and relatively intact biotic communities (Golladay et al., 2004). Upland forested land in the region is composed of 44% evergreen conifer forest, and 56% broadleaf hardwood or mixed hardwood-conifer forest (National Land Cover Database, 2011; Homer et al. 2015). The majority (~80%) of conifer forest is high-density commercial loblolly pine (*Pinus taeda* L.) or slash pine (*Pinus elliottii* Engelm.) plantation (Martin et al., 2012). The remaining 20% of evergreen conifer forest (about 3% of the entire watershed) is low-density longleaf pine (*Pinus palustris* Mill.) (Martin et al., 2012), and is primarily managed for bobwhite quail (*Colinus virginianus*) hunting, protection of endangered species, aesthetic value, or a combination of uses.

2.2 Model description

The Soil and Water Assessment Tool (SWAT) was used to evaluate the potential effect of large-scale longleaf pine restoration to affect streamflow in the INC watershed. Specifically, we simulated the conversion of ~95,000 ha of high-density evergreen conifer and mixed-species forest to longleaf pine woodlands. SWAT is a continuous-time, semi-distributed, process-based watershed model developed by the USDA Agricultural Research Service (Douglas-Mankin et al., 2010; Arnold et al., 2012). SWAT has been used successfully to represent watersheds with land use changes (Neitsch et al., 2011), including afforestation (Cecilio et al., 2019) and deforestation (Kavian et al., 2017).

SWAT input data included land use (including crop and forest type), topography, soil classification, daily climate, and crop management (i.e., dominant crops and irrigation schedules). The watershed boundary was delineated using ArcGIS 10.3 with the ArcSWAT 2012.10.19 extension (Winchell et al., 2007). Digital elevation models obtained from U.S. Geological Survey National Elevation Dataset at the resolution of 1/3 arc-second were used as topographic input data (https://lta.cr.usgs.gov/NED). The watershed was divided into 25 subbasins based on topography, with sizes ranging from 10 to 190 km^2. Each subbasin was further divided into hydrological response units (HRU), as each HRU was a unique combination of soil, land use, and topography class. Soil input data was from the State Soil Geographic database (STATSGO, *Soil Survey Staff*, 2017) for Georgia. Soil texture ranges from loam to sand, with 95% of soil having >50% sand. The dominant soil hydrologic group is B, covering 70% of the area. Daily maximum and minimum temperature and precipitation data were obtained from four weather stations maintained by the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net) and seven stream gages operated by the U.S. Geological Survey within the watershed (https://waterdata.usgs.gov/nwis) (Fig. 1). Weather data were applied to subbasins automatically by ArcSWAT based on station proximity. Potential evapotranspiration was calculated by SWAT using Penman-Monteith method.

Land use input data was sourced from the National Land Cover Database 2011 (Homer et al., 2015). Land use types were further refined to better reflect actual land cover types where possible. The agriculture (AGRL) land use type was split into corn, cotton, and peanut, with cotton and peanut each occupying 40% of agriculture land and corn occupying the remaining 20%. Although these values change from year-to-year, these percentages reflect long-term trends in land use typical in the region (Hook et al., 2005). The base SWAT model also uses land cover inputs to separate upland forests (as distinguished from forested wetlands) into two land cover types based on tree functional group dominance. Henceforth, these groups are designated as evergreen (FRSE) and mixed forest (FRST). For the purposes of this study, an especially important distinction was differentiating longleaf pine from other evergreen conifer forests in the model. Evergreen forest (FRSE) was split into two forest types: longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.). For this model version, loblolly pine was randomly assigned to ~80% of FRSE. For the remaining evergreen conifer forest, we created a third forest type, designated FRLL, to represent longleaf pine in the baseline model. This new forest type was also used in the simulated restoration model.

We adjusted parameters that govern forest ecosystem processes including potential plant growth, leaf area development, and evapotranspiration (Table1). For example, mixed pine-hardwood forests in this region tend to have higher leaf area index (LAI) and a relatively large component of evergreen or semi-deciduous oaks when compared to the forests represented in the model (Table 1). Several parameters were adjusted for all forest land cover types to better represent forest structure and function in the region based on an earlier sensitivity analysis of the model (Qi et al., 2020) and on a working knowledge of the longleaf pine ecosystem and associated forests. For potential plant growth, these parameters included radiation-use efficiency (BIO_E) and maximum canopy height (CHTMX) (Arnold et al., 2013; Qi et al., 2020). For leaf area development, four parameters defining the optimal leaf area development curve were adjusted: maximum potential leaf area index (BLAI), fraction of growing season when leaf area begins to decline (DLAI), fraction of the plant growing season (FRGRW1), and fraction of the maximum leaf area index (LAIMX1) corresponding to the first point on the optimal leaf area development curve (Arnold et al. 2013; Qi et al. 2020). DLAI of mixed forest was smaller than loblolly pine and longleaf pine to reflect the deciduous species in the mixed forest. Because longleaf pine is known for deep taproots, parameter RDMX, maximum rooting depth, for longleaf pine was adjusted to 3.5 m, the maximum depth allowed in the model. Parameter BLAI was adjusted to two for longleaf pine woodland to represent the open canopy structure of this forest type. These input parameters are summarized in Table 1.

Other parameters previously identified as sensitive by Qi et al. (2020) included three values related to stomatal conductance. Stomatal conductance to water vapor (g_s) is used in Penman-Monteith calculations of maximum plant evapotranspiration for each forest type. To better represent the physiology of longleaf pine and differentiate it from loblolly pine and broadleaf forest, three parameters were adjusted based on new field data from a portable photosynthesis system (Li-6400XT, Li-Cor Inc., Lincoln, NE, USA). Field measurements were conducted in planted pine stands at the Jones Center at Ichauway (www.jonesctr.org), located within the study area at the confluence of the INC and Flint River (31.22 N, 84.48 W). To derive the parameters, we measured relationships between g_s and vapor pressure deficit (VPD) during the 2018 growing season. Measurements were conducted between sunrise and late morning on bright days in late spring and summer after full leaf-out. All measurements were taken 1–2 days after rain events to minimize any effects of soil moisture limitation on maximum g_s. For each species, we selected 20 individual branches growing in full sunlight. Light was set to 1000 µmol m^{-2}-s^{-1} and CO_2 was set to 400 ppm. We allowed leaf temperature to fluctuate due to the difficulty of controlling it in the hot summer conditions (air temperature was generally >30 °C). Vapor pressure deficit (VPD) was manipulated on the instrument by slowly opening or closing the moisture scrub controls, starting with high humidity conditions and adjusting towards lower humidity with each measurement. Targeted VPD values were between 1 and 4 kPa. After each adjustment, a reading was taken after g_s had stabilized. For each species, three parameters were extracted from the g_s-VPD curve for each species: maximum leaf stomatal conductance (GSI), fraction of maximum stomatal conductance (FRGMAX), and vapor pressure deficit (VPDFR=4 kPa) corresponding to the second point on the stomatal conductance curve (Arnold et al., 2013).

2.3 Model calibration and validation

We used two U.S. Geological Survey streamflow gages for calibration and validation: Ichawaynochaway Creek at Milford (02353500) and Ichawaynochaway Creek below Newton (02355350) (https://waterdata.usgs.gov/nwis). The Milford stream gage, henceforth the upper gage, drains an area of approximately 1600 km^2 in the Fall Line Hills physiographic region of the upper coastal plain. The below-Newton stream gage, henceforth the lower gage, drains nearly the entire watershed, including a large area of the Dougherty Plain physiographic region (Fig. 1). Climate data from 1990 to 2016 were used for model calculation, with a spin-up period from 1990 to 2000 to minimize the influence of initial states (Arnold et al. 2013). Streamflow data from 2009 to 2016 were used for model calibration because there were more climate data available for this period and the land cover input data more closely resembled current land use. Model validation utilized stream data from 2001 to 2008. Calibration and validation periods represented several extremes across the longer record, including the extreme drought periods of June to November 2007, and June 2011 to July 2012 (Palmer drought severity index <-4); and the extreme wet periods of July to August 2005, January 2010, August to September 2013, and April 2014 (Palmer drought severity index >4) (Qi et al., 2020).

The model was calibrated against observed streamflow by adjusting relevant input parameters governing surface runoff and baseflow based on initial model performance and suggestions from previous research (Arnold et al., 2012; Abbaspour et al., 2015; Qi et al., 2020). See Qi et al. (2020) for a full description of model calibration and validation using SWAT-CUP (Arnold et al., 2012; Abbaspour et al., 2015). The model was first calibrated for the upper gage, then calibrated for the lower gage including adjusted parameters for the upper watershed (Table 2). The simulation results were evaluated based on Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), ratio of the root mean square error to the standard deviation of measured data (RSR), and R^2 (Moriasi et al., 2007). Model evaluation was based on guidelines from Moriasi et al., (2007). Model performance ratings in the range of “good” and “very good” (Moriasi et al., 2007) were accepted for further analysis.

2.4 Longleaf pine restoration scenario

We used the calibrated SWAT model to evaluate the potential effects of large-scale longleaf pine restoration on streamflow. A baseline scenario reflected current land use and served as a reference for comparing hydrologic responses after longleaf restoration (treatment scenario). A longleaf pine restoration scenario converted ~95,000 ha, or 32% of total watershed area, to open-canopy longleaf pine woodland. This was in addition to the 3% of watershed area already in longleaf pine. Only previously forested land cover was converted. No row crop agriculture, urban, or wetland land use types were converted to longleaf pine to minimize conflict with other economic or environmental priorities. Streamflow volumes for baseline and treatment scenarios were converted into water yield (depth) by dividing streamflow by watershed area to better compare with measured precipitation and modeled evapotranspiration values. We also compared modeled ET estimates for each land cover type to ensure the parameter changes had the intended effect on the new FRLL classification.

To help verify the effects of our revised forest parameter estimates, we compared annual modeled ET of various land cover types. Values were compared against annual precipitation over the study period to illustrate the interactions between land cover, ET, and water yield. To quantify the effects of simulated forest restoration on monthly streamflow, we used a frequency pairing analysis method where we constructed flow duration curves for the baseline and restoration scenarios. This method ranks flow periods (e.g. months) in ascending order, and either relies on direct comparisons of flow during similar hydrologic conditions (e.g., flow at 5%, 25%, or 50% exceedance probability), or it allows comparisons of changes in probability of a specific flow rate occurring (Alila et al., 2009; Brantley et al., 2015; Qi et al., 2020). Median flow (50% exceedance probability) provides an estimate of central tendency and relates well to other metrics such as mean annual streamflow and yield. Flow at the 25^{th} exceedance probability represents a recognized state of "low flow" where hydrologic drought conditions start to occur. The 5^{th} exceedance probability represents a state of "extremely low flow" where water supplies are threatened, and ecosystem function may be severely impaired. Lastly, we compared absolute and relative changes in flow during specific periods of the hydrologic cycle. Although this type of "chronological pairing" has limitations in terms of objectively quantifying streamflow changes (Alila et al., 2009), these comparisons are often more intuitive for many readers and may be of interest to stream ecologists.

3 Results

3.1 New model parameters

Stomatal conductance in loblolly pine and longleaf pine each showed a negative relationship with VPD (Fig. 2). The slopes of the g_s-VPD response curves did not differ significantly (p=0.27) between loblolly pine and longleaf pine (Fig. 2). However, the correlation between stomatal conductance and VPD was stronger for longleaf pine (R^2=0.35) than loblolly pine (R^2=0.11), which is indicative of tighter coupling between atmospheric water demand and stomatal response for longleaf pine under the soil conditions sampled here. The maximum stomatal conductance value observed for loblolly pine (0.37 mol H_2O $m^{-2}s^{-1}$) was higher than longleaf pine (0.30 mol H_2O $m^{-2}s^{-1}$) (Fig. 2; Table 1). Leaf-level g_s values were converted to GSI (m/s) for the model (Table 1). FRGMAX values were extracted based on the stomatal conductance curves at VPD=4 (Arnold et al. 2013). FRGMAX of longleaf pine (0.43) was lower than loblolly pine (0.64); while mixed forest had the largest value (0.75, Table 1).

3.2 Calibration and validation

For the calibration period (2009-2016), model performance for the upper gage was very good regarding NSE (0.83), and RSR (0.41) and was very good in the bias between model estimation and observation for mean monthly streamflow (PBIAS=14.4%). For the lower gage, the NSE (0.86), RSR (0.38), and PBIAS (1.9%) were all in the range of very good performance (Moriasi et al., 2007). During the validation period (2001-2008) the model generated good results with NSE=0.69 for the upper gage and NSE=0.77 for the lower gage. PBIAS was relatively small with satisfactory performance for the upper stream gage (PBIAS=20.4%) and good performance for the lower gage (PBIAS=9.0%). The root mean square error to the standard deviation of measured data (RSR) were also good for the upper (RSR=0.56) and lower gages (RSR=0.50) (Moriasi et al., 2007) (Table 3). The magnitude of differences between observed and simulated streamflow was small and monthly flow in both the simulated and actual stream never reached zero. The 95% prediction uncertainty range covered 65% of data for the upper gage and 59% of data in the lower gage (Fig. 3).

3.3 Annual water budget

Within the modeling period of 2001 to 2016, annual precipitation ranged from 881 to 1615 mm, versus a long-term average of 1310 mm (Fig. 4). Modeled ET was positively correlated with precipitation for all land cover types, although ET did not increase proportionally with rainfall (Fig. 4). Among major vegetation land uses, agriculture generally had the highest ET, followed by loblolly pine, mixed forest, and lastly, longleaf pine (Fig. 4). Mean annual longleaf woodland ET was 31mm less than mixed forest, 65 mm less than loblolly pine forest, and 133 mm less than agriculture fields (Fig. 4). While the absolute difference in ET between longleaf and other forest types was stable across the range of annual rainfall observed, the relative difference in ET between longleaf pine and other forest types was greatest during the driest year. Longleaf pine transpired 129 mm less water than agriculture fields, equivalent to 14% of total precipitation received during the driest year (Fig. 4). Modeled ET of longleaf pine ranged from 703 to 828 mm. That 703 mm was 80% of precipitation in the driest year (2011). In the same year, the ET of agriculture, loblolly pine, and mixed forest, were 832, 763, and 753 mm, corresponding to 94%, 87%, and 86% of precipitation. During the year of highest precipitation (2013), ET of agriculture accounted for 58% of precipitation, while longleaf pine 50% (Fig. 4). As a result of lower ET, the simulated conversion of 32% of the watershed from other forest types to longleaf pine resulted into an increase in water yield of 17.9 mm, or +5.2% water yield. This included a 17.2 mm increase in streamflow and a 0.7 mm increase in deep aquifer recharge, according to the model. The annual volume equivalent for changes in streamflow was +53 million m^3.

3.4 Monthly streamflow effects

Longleaf pine restoration had a positive impact on monthly flow over a wide range of hydrological conditions at both the upper and lower gages (Figs. 5 & 6). Median flow increased from 8.0 to 11.3 m^3/s at the upper gage and from 20.4 to 23.2 m^3/s at the lower gage. Absolute changes in flow were generally higher as flow increased, except for extremely high flows, which did not change or decreased. At the upper gage when flow exceeded 47 m^3/s, or 94th exceedance probability, simulated absolute flow was similar to or lower than the control scenario (Fig. 5). The reductions in flow were small, at less than 10%.

The impact of longleaf pine restoration was relatively stronger during low flow and low precipitation periods (Fig. 5 & 6). Longleaf pine restoration consistently increased flow in the extreme low flow situation (5th exceedance probability). At the upper gage, a mean monthly flow of <1 m^3/s (7.1% exceedance probability) occurred during 14 months under the original land use scenario; but that number decreased to 9 months (4.5% exceedance probability) under the longleaf pine restoration scenario (Fig. 5). At the lower gage, longleaf pine restoration raised 5th exceedance probability flow from 1.5 m^3/s to 1.8 m^3/s (Fig. 5). Relative flow changes—i.e. change in flow as a percentage of baseline flow—were also highest during low flow conditions (Fig. 5). The greatest flow response was the 6th exceedance probability flow at the upper gage with a 74% increase (+0.5 m^3/s); while the 6th exceedance probability flow at the lower gage had a 29% increase (+0.5 m^3/s) (Fig. 5). When comparing flow to precipitation on an annual time series, the greatest response to longleaf pine restoration occurred during low precipitation months (Fig. 6). Averaged over the 16-year modeling period, there were three months during the growing season:

May, September, and October, when precipitation was below 100 mm. At the upper gage, longleaf pine restoration increased flow from 12.1 to 15.8 m^3/s (30.1±7.3% increase) during May, and from 5.6 to 8.6 m^3/s (51.7±9.4% increase) during October. At the lower gage, longleaf pine restoration increased flow from 11.5 to 12.6 m^3/s (10.2±1.9% increase) during May, and from 7.6 to 8.6 m^3/s (14.3±1.8% increase) during September (Figure 6). When monthly cumulative precipitation was <100 mm, longleaf pine restoration increased flow as much as 52% at the upper gage and 14% at the lower gage (Fig. 6). Within the simulation period, low flow often started in May and lasted until November, despite high precipitation months of June, July, and August (Fig. 6).

4 Discussion

4.1 Implications for water yield

It is generally accepted that forests are the best land cover for providing clean water, mitigating flood risks, and supporting a stable baseflow (Burt & Swank, 2002; Kaimowitz, 2005; Robinson et al., 2003; Neary et al., 2009; Qazi et al., 2017). However, evapotranspiration also makes up a major proportion of the water budget in terrestrial ecosystems, and can have a significant impact on water availability (Trenberth et al., 2007). High tree density and leaf area index can translate into high ET, and subsequent low water yields (Asner et al., 2003; Jackson et al., 2005; McLaughlin et al., 2013). Reforestation and afforestation can reduce water yield when ET increases above pre-treatment levels after forest regrowth (Burt & Swank, 2002; Farley et al., 2005; Trimble & Weirich, 1987; Ford et al., 2011). Changes in watershed vegetation cover that result in increased leaf area and/or a shift in species composition from more water-conservative species to more water-consumptive species can result in lower water yield (Bosch & Hewlett, 1982; Brown et al., 2005; Jackson et al., 2005; Ford et al., 2011; Caldwell et al., 2016). For example, water yield may decrease due to forest mesophication, or the transition of forests from fire tolerant to fire-intolerant species (Nowacki & Abrams, 2009; Caldwell et al., 2016). In more extreme cases, such as afforestation, the effects can be larger (Waterloo et al., 1999; Zhou et al., 2002). A systematic global analysis of 26 catchments noted that, on average, afforestation of previous grass- and shrublands reduced annual runoff by 44% and 31%, with greater impact on low flow and on drier sites (Farley et al., 2005). For watershed managers, this balance between forest water use and runoff can be used to mitigate flood risk, reduce soil erosion, and improve water quality. It might also be used to increase water yield (Douglas, 1982).

In our study, simulated longleaf pine restoration increased streamflow over a wide range of hydrologic conditions, and especially during low precipitation and low flow periods. The increase in yield was a direct result of reducing watershed ET by replacing other forest types with low-density longleaf pine. Frequently burned longleaf pine woodland has an open canopy and sparse midstory, and therefore has a lower leaf area than other forest types in the region, resulting in relatively low ET (Ford et al., 2008; Whelan et al., 2015; Brantley et al., 2017). In addition, longleaf pine stomatal conductance is generally more responsive to water limitations than loblolly pine and/or slash pine (Gonzalez-Benecke et al., 2011; Novick et al. 2016). These two characteristics are reflected in the plant growth parameters we manipulated in the SWAT model. As expected, modeled ET of longleaf pine land cover was less than row crops, pasture, mixed species forests, or dense loblolly pine. At the watershed scale, the resulting lower ET of longleaf pine translated into more residual rainfall being available for streamflow. The relative difference in streamflow between longleaf pine and other forest types was greatest during the driest year. This is likely because of the characteristics of longleaf pine's sensitivity to drought compared to other tree species. As a result, wide-scale longleaf restoration increases streamflow in general, and increases low flows specifically. It should also be noted that longleaf restoration did not have a large impact on high flows. When streamflows were high, simulated longleaf pine restoration reduced streamflows compared with control scenario, although the reductions in flow were small, at less than 10%. A possible explanation for this is the model has reached its storage capacity with high rainfall inputs and consequently, high flows. In this situation, streamflows responded to rainfall-runoff, not changes in land use or evapotranspiration.

4.2 Implications for aquatic systems

The addition of relatively small amounts of water during dry periods suggested by our simulations could have important implications for stream health in this basin, and throughout the southeastern US. Past decreases in streamflow during the growing season and during extended droughts has had substantial effects on aquatic fauna of the region including fishes, freshwater mussels, and crayfishes (e.g., Golladay et al., 2004; Sargent et al., 2011; Freeman et al., 2013; Smith et al., 2017; & Davis et al., 2020). Increasingly, streams within the lower Flint River Basin are ceasing to flow during growing season dry periods with only isolated pools remaining (e.g., Gordon et al., 2012; Smith et al., 2017; Davis et al., 2020). While the comprehensive effects on stream ecosystems are not known, studies of important faunal groups show the potential severity of changing flow regimes. Golladay et al. (2004) showed declines and population extirpation of both common and federally listed freshwater mussel species during stream drying in the lower Flint. Mussels serve an important foundational role in stream food webs; thus, their loss diminishes nutrient cycling and secondary production (Atkinson et al. 2018, Dubose et al. 2019). Because freshwater mussels are long-lived with complex life cycles, reestablishing populations following extirpation may require decades if stream drying frequency exceeds population resiliency (Dubose et al., 2019).

Other taxonomic groups may also benefit from additional streamflow from longleaf restoration. Aquatic arthropods (insects and crustaceans) fill a similar role as freshwater mussels in southeastern streams, being primary consumers of basal resources and providing biomass to higher trophic levels, but the effects of stream drying on regional freshwater arthropods is not well studied. Smith et al. (2017) noted that intermittent streams had lower taxa richness than streams with perennial flow. Declines in aquatic insect taxa with annual or longer life histories were also noted and attributed to inadequate time for life cycle completion (Smith et al., 2017). Like mussels, loss of arthropod diversity likely diminishes nutrient cycling and trophic support. Fish species also show complex responses to stream drying. Because of high mobility, many species respond by migrating to perennial refugia. Using landscape models, Freeman et al. (2013) showed that local species richness recovered rapidly following drying. However, Davis et al. (2020) noted that increased frequency and duration of stream drying may not provide adequate time for reproduction and larval development of some common fish species, suggesting the potential for longer term declines in fish species diversity. Overall, water scarcity threatens biotic richness with possible cascading effects for stream ecosystem function, particularly during the growing season. In effect, factors that affect these communities also affect water quality because of the loss of assimilative capacity provided by the healthy in-stream community, and point to an even greater need to maintain or restore streamflow.

4.3 Strategies for longleaf restoration

While this simulation study shows promising results for improving water yield and sustaining streamflow during droughts, these results must be considered in the context of real-world forest and watershed management. First, our simulations directly replaced existing forest types with mature, low basal area longleaf. Real-world restoration to achieve mature, functional longleaf pine can often take many decades, especially when cutting down existing forest and planting longleaf pine is necessary. Future studies are needed to simulate the effects of cutting and planting on water yield, as well as flood risks and water quality. Second, and perhaps more importantly, we should consider how realistic it is that ~30% of this watershed would be converted to longleaf pine woodland. Our simulation increased longleaf pine cover in the watershed nearly 10-fold. While this is still likely short of historic longleaf cover in this watershed (50-80%), achieving this scale of change would be challenging considering the costs of restoration and the competing land uses. Still, one the major goals of America's Longleaf Restoration Initiative is to increase the cover of longleaf pine-dominated stands from ~1.7 million ha to 3.2 million ha by 2025 (ARLI 2009). Because not all areas where longleaf occurs are ideal for restoration, and not all areas show a need for this type of concentrated conservation for ecosystem services, the INC watershed might be considered a priority area where restoration efforts would be more focused. And future research should be dedicated to targeting/prioritization of areas most suitable to influence hydrology, both within the INC watershed, and in other watersheds in the region.

While restoring some forest stands to longleaf pine would take many decades, two strategies might help accelerate restoration at a scale large enough to be meaningful for streamflow. The first strategy would be to leverage already-scheduled harvesting of short-rotation loblolly or slash pine plantations, and incentivize replanting with longleaf, either through market development of longleaf pine products such as straw, conservation policies that promote longleaf restoration, or both. The second, and perhaps quicker and more economical strategy, would be to identify and restore existing mixed pine-hardwood forest that have a relic component of longleaf pine. Many forested stands that were once low-density longleaf pine have changed due to a lack of fire (Brantley et al. 2017). While the overall structure (increased density and leaf area) and species composition has changed, many of these stands retain a longleaf pine component which can serve as the foundation for the type of longleaf woodland we simulated (Guldin et al., 2016). Because longleaf woodland is a low-density ecosystem, relic longleaf pine can comprise a "minor manageable component" that can serve as the core for restoration with considerably less effort, time, and cost than cutting and planting (Guldin et al., 2016). By thinning out hardwoods and other pine species, and reintroducing prescribed burning, these stands can be converted to longleaf dominated stands which resemble the structure and function of intact longleaf woodland (Guldin et al., 2016). Even in stands where longleaf pine is a minority of pine, other pine species can help maintain the structure and fire regime, and have some benefit to water yield. If longleaf pine dominance is desired, slowly replacing other pines through underplanting of longleaf seedlings is a proven method of stand conversion (Jack et al., 2005; Kirkman & Giencke, 2017), and this method of forest management would reduce potential issues with water quality associated with cutting and planting.

4.4 Conclusions

Recent severe droughts in the southeastern U.S. coupled with increasing water demands have necessitated creative solutions for addressing regional water scarcity. Because row crop agriculture is the largest water user in the region, the vast majority of water conservation efforts have focused on reducing agricultural water use. Our previous modeling efforts in the Ichawaynochaway creek watershed showed that reducing irrigation volume can enhance water yields with a larger effect during low flow periods (Qi et al. 2020). The current study demonstrates than longleaf restoration may be just as effective as irrigation reduction at improving water yield. Forest hydrology has long been considered an important tool for watershed management and water-centric forest management offers a promising strategy to help sustain water supplies (Douglas, 1982; Ford et al., 2011; McLaughlin et al., 2013; Brantley et al., 2017). Restoration of longleaf pine forests, coupled with implementation of the latest agriculture water-saving technologies could have substantial impact on water yield and help mitigate water scarcity in the southeastern US, especially during drought.

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Table 1. To represent forest in the region, several parameters of mixed forest (FRST) were adjusted, and evergreen forest (FRSE) was split into two forest types: longleaf pine (FRLL; *Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.). Leaf area development parameters included maximum potential leaf area index (BLAI), fraction of growing season when leaf area begins to decline (DLAI), fraction of the plant growing season (FRGRW1) and fraction of the maximum leaf area index (LAIMX1) corresponding to the first point on the optimal leaf area development curve. Stomatal conductance parameters included maximum stomatal conductance (GSI), vapor pressure deficit (VPDFR) and the fraction of maximum stomatal conductance (FRGMAX) corresponding to the second point on the stomatal conductance curve. Other parameters were biomass-energy ratio (BIO_E), maximum canopy height (CHTMX), maximum root depth (RDMX).

		Forest type		
Processes	Parameters	Longleaf Pine	Loblolly Pine	Mixed Forest
Plant growth	BIO_E ((kg/ha)/(MJ/m^2))	75	75	75
	CHTMX (m)	20	20	20
	RDMX (m)	3.5	2	2
Leaf area development	BLAI (-)	2	6	6
	DLAI (-)	0.99	0.99	0.8
	FRGRW1 (-)	0.1	0.1	0.1
	LAIMX1 (-)	0.7	0.7	0.3
Stomatal conductance	FRGMAX (-)	0.43	0.64	0.75
	GSI (m/s)	0.002	0.002	0.002
	VPDFR (kPa)	4	4	4

Table 2. Model parameters adjusted for calibration for the upper and lower watersheds. Parameters that govern surface runoff were soil conservation service runoff curve number (CN2), soil evaporation compensation factor (ESCO), and available water capacity of the soil layer (SOL_AWC). Parameters that govern baseflow were baseflow alpha factor (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), and groundwater re-evaporation coefficient (GW_REVAP).

Process	Parameters	Method	Upper Watershed	Lower Watershed
Surface Runoff	CN2	Relative	-0.15	-0.15
	ESCO	Replace	0.85	0.9
	SOL_AWC	Relative	0.4	0.4
Baseflow	ALPHA_BF	Replace	0.53	0.3
	GWQMN	Replace	4200	2500
	GW_REVAP	Replace	0.025	0.025

Table 3. Summary of model performance for calibration and validation. Two stream gages were used: Ichawaynochaway Creek at Milford (02353500, the upper gage) and Ichawaynochaway Creek below Newton (02355350, the lower gage). The calibration results were evaluated based on Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), ratio of the root mean square error to the standard deviation of measured data (RSR), and R^2. Calibration period: 2009-2016. Validation period: 2001-2008. Calculation and validation were performed with Sequential Uncertainty Fitting (SUFI-2) algorithm using SWAT-CUP.

	Gage Station	R^2	NSE	PBIAS (%)	RSR
Calibration	Upper gage	0.88	0.83	14.4	0.41
	Lower gage	0.86	0.86	1.9	0.38
Validation	Upper gage	0.79	0.69	20.4	0.56
	Lower gage	0.75	0.77	9.0	0.50

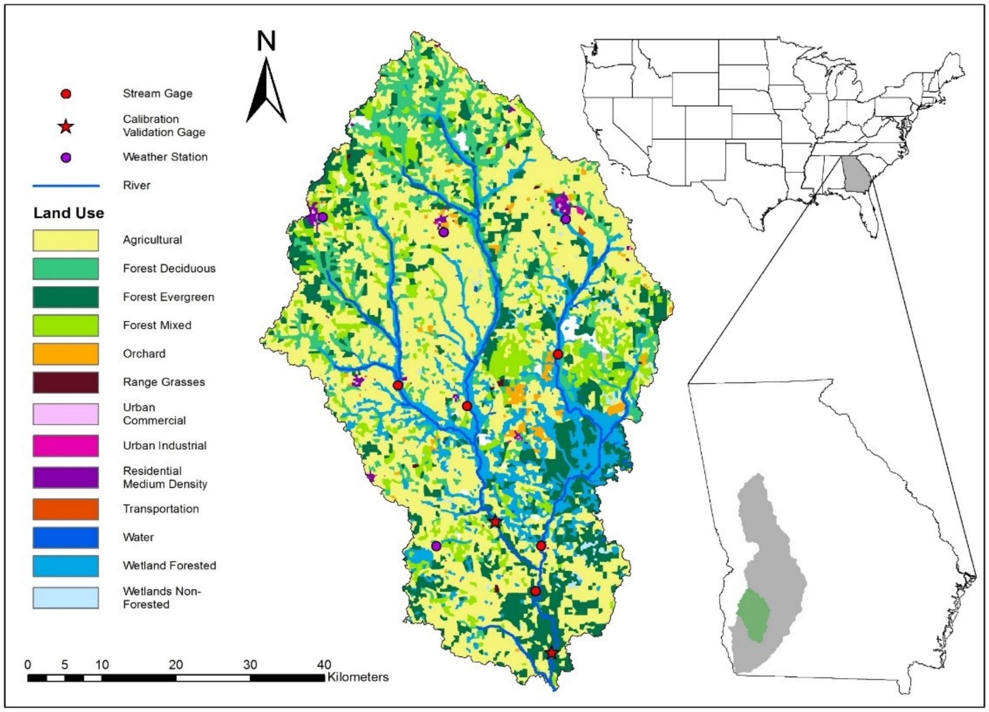

Figure 1. The Ichawaynochaway Creek watershed is part of the Flint River watershed (gray area) in the state of Georgia, USA. Land use of the watershed is dominated by agriculture (50%) with remaining acreage in forestland (35%), wetlands (14%) and urban area (1%) (National Land Cover Database 2011, Homer et al. 2015). Weather stations maintained by Georgia Automated Environmental Monitoring Network by the College of Agricultural and Environmental Sciences of the University of Georgia (www.georgiaweather.net) provided daily precipitation and maximum and minimum temperature data. Stream gages operated by U.S. Geological Survey (https://waterdata.usgs.gov/nwis) provided additional precipitation data (red circles and red stars). Data from two stream gages (red stars) were used for model calibration and validation.

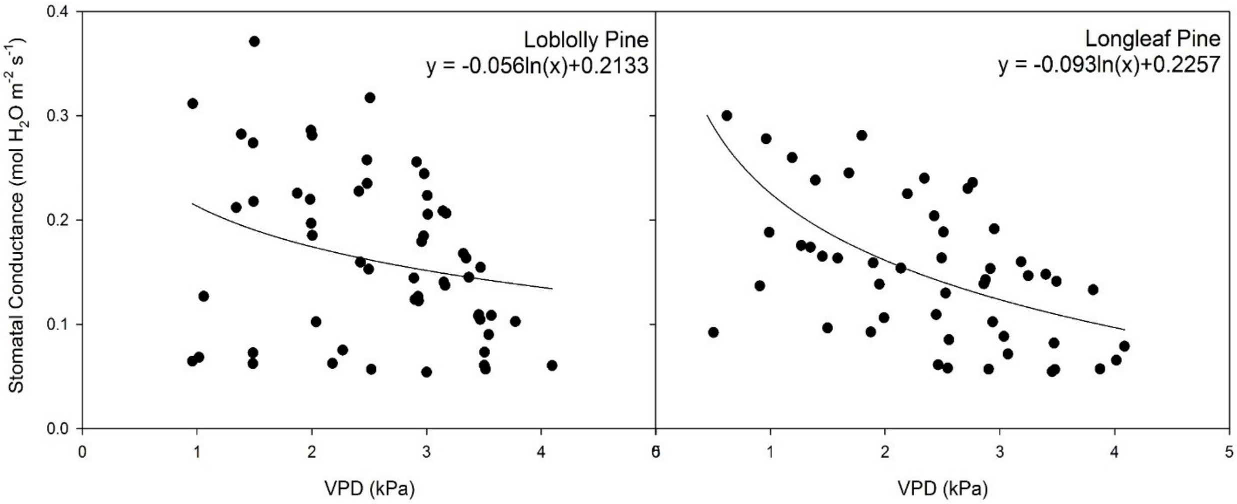

Figure 2. Leaf stomatal conductance (mol H_2O m^{-2} s^{-1}) in response to vapor pressure deficit (kPa) curves of longleaf pine and loblolly pine. Data points were generated using Li-6400XT equipped with 6400-40 leaf chamber fluorometer (Li-Cor Inc., Lincoln, NE, USA) during 2018 growing season. Measurements were conducted between sunrise and late morning on bright days in late spring and summer after rain events.

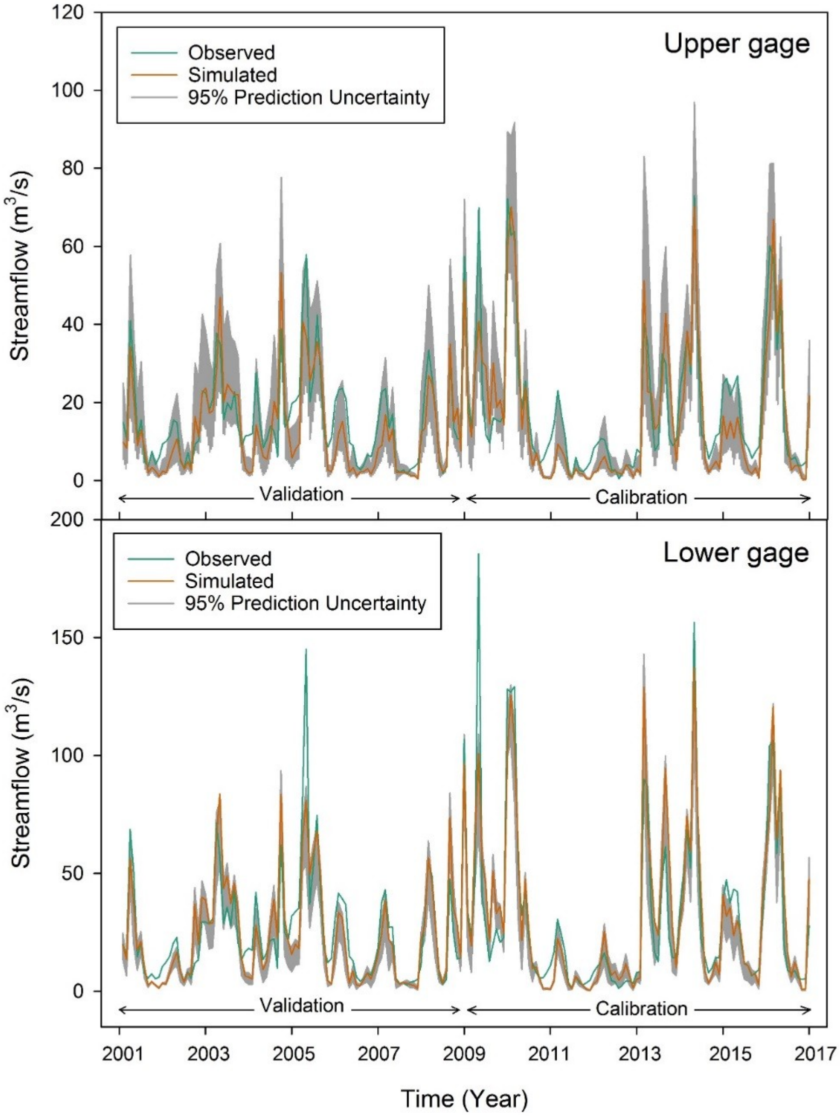

Figure 3. Calibration and validation for monthly streamflow during the study period of 2001 to 2016. Calibration period: 2009-2016. Validation period: 2001-2008. Two stream gages were used: the upper gage (Ichawaynochaway Creek at Milford 02353500, top panel), and the lower gage (Ichawaynochaway Creek below Newton 02355350, bottom panel).

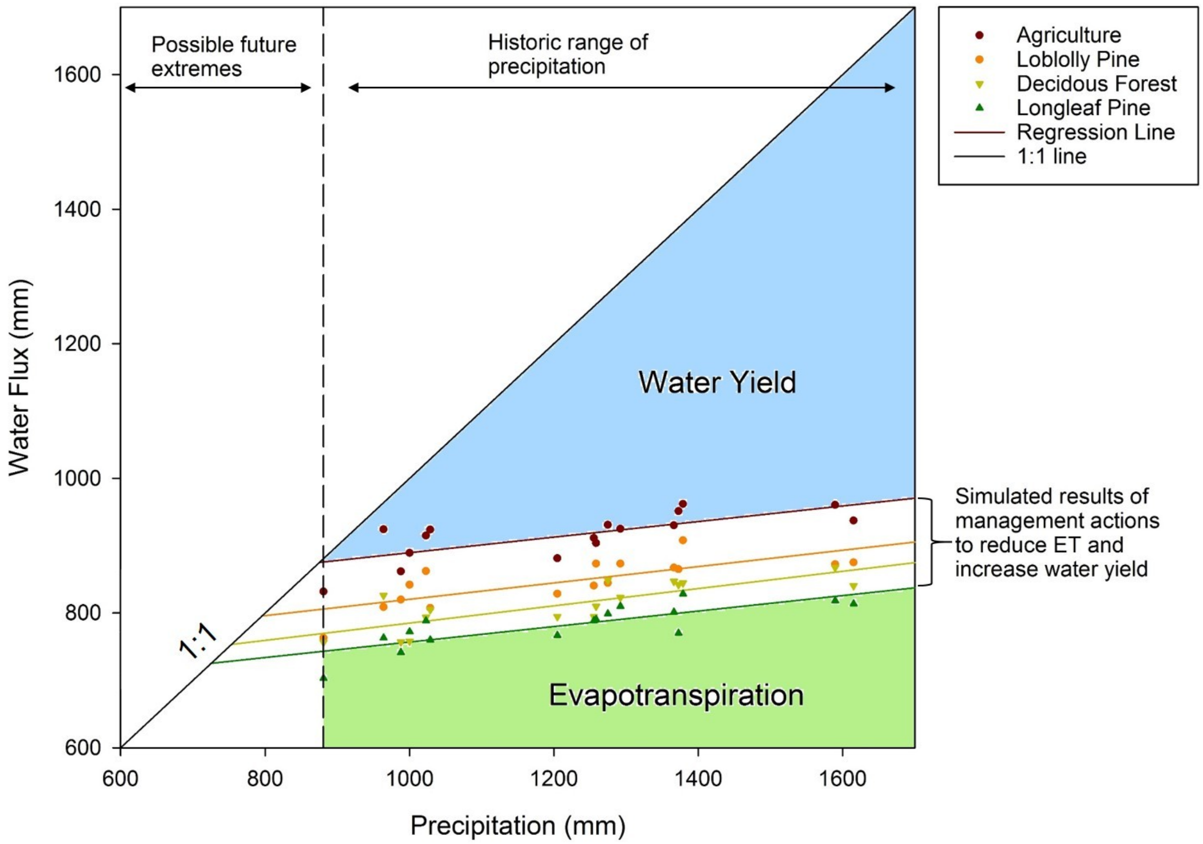

Figure 4. Annual water budget with evapotranspiration rate of land use types under the range of observed precipitation from 2001 to 2016. Data points represent evapotranspiration of four land use types: agriculture (brown), loblolly pine (orange), mixed forest (yellow), and longleaf pine (green). Linear regression lines were fitted for each corresponding land use. The 1:1 line marks the precipitation equals to evapotranspiration plus water yield. Dashed line marks the lowest annual precipitation within the modeling period. Figure adapted from Oishi et al. 2010.

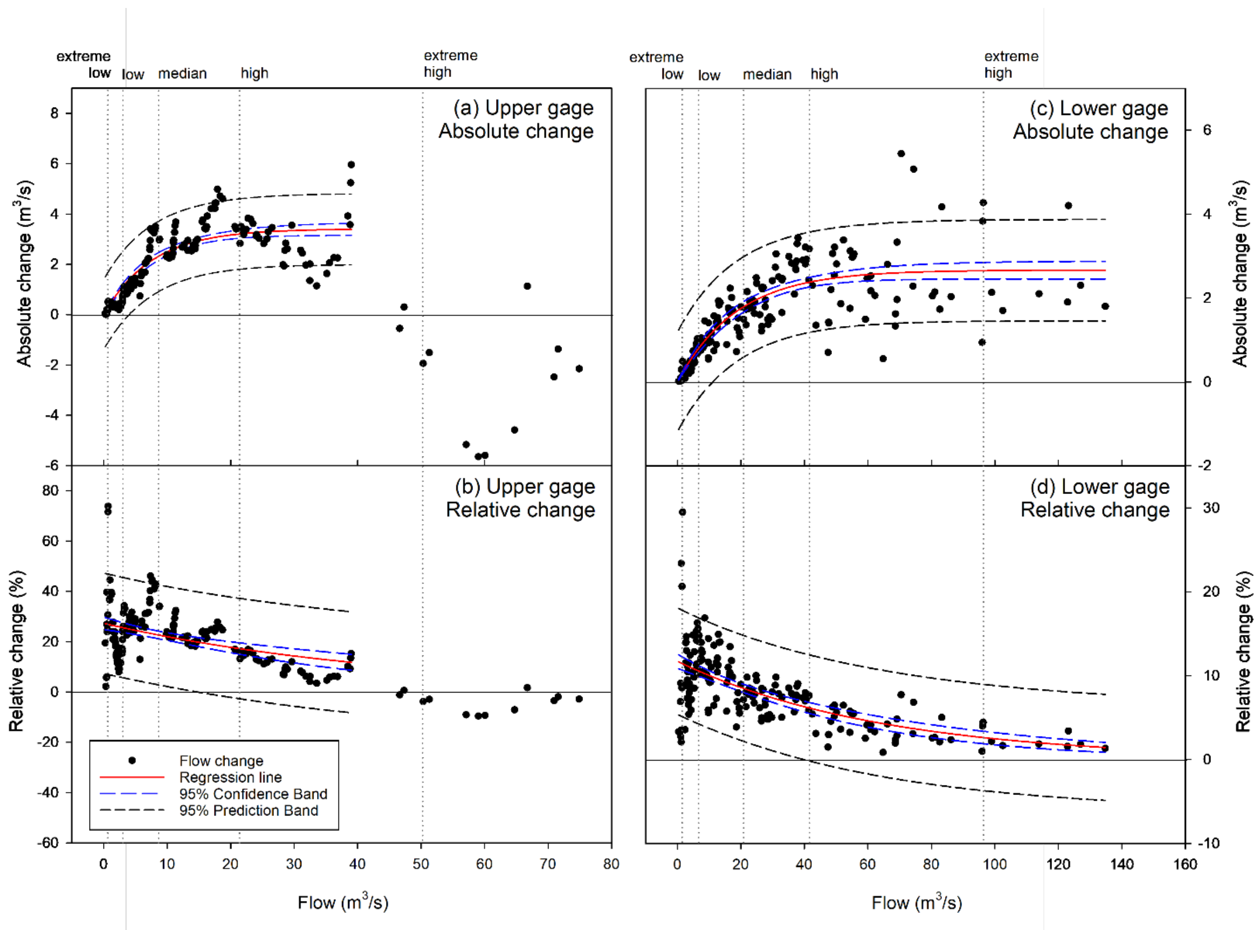

Figure 5. Simulated monthly streamflow responses to longleaf pine restoration versus a baseline scenario for two stream gages on the Ichawaynochaway creek: the upper gage (Ichawaynochaway Creek at Milford, 02353500, left panels) and lower gage (Ichawaynochaway Creek below Newton, 02355350, right panels). Absolute change (top panels) and relative change (bottom panels) are shown, and natural log regressions are fitted to the data. Extremely low flow (5th exceedance probability), low flow (25th exceedance probability), median flow (50th exceedance probability), high flow (75th exceedance probability), and extreme high flow (95th exceedance probability) are shown. Note that equations were not fitted to extreme flow data for the upper gage (see text).

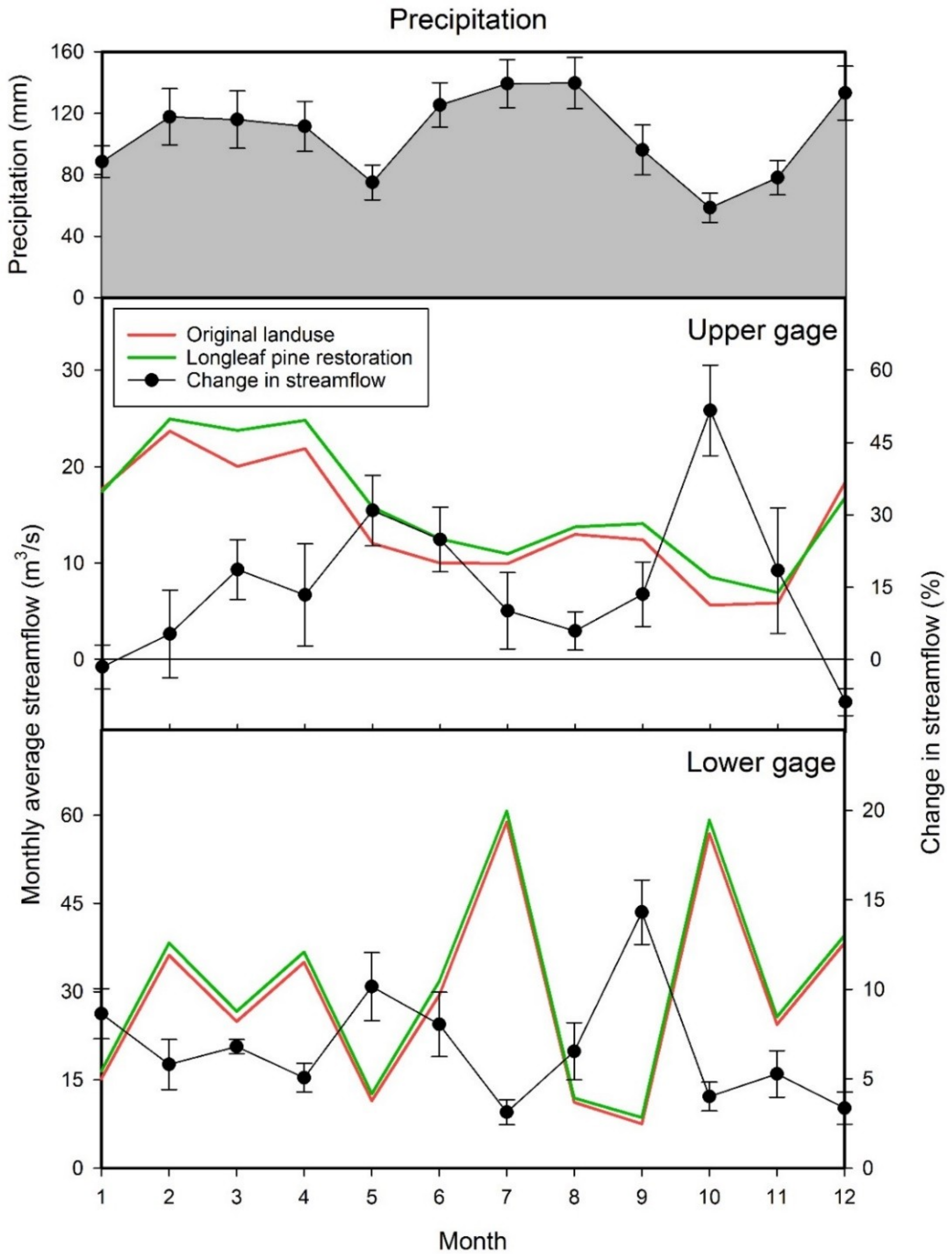

Figure 6. Monthly flow on annual scale under baseline (red line) and longleaf pine restoration (green line) scenarios paring with precipitation. Top panel shows monthly average precipitation over the model period from 2001 to 2016. Precipitation data were obtained from weather stations maintained by Georgia Automated Environmental Monitoring Network by the College of Agricultural and Environmental Sciences of the University of Georgia (www.georgiaweather.net) U.S. Geological Survey (https://waterdata.usgs.gov/nwis). Middle (upper gage) and bottom panels (lower gage) show flow responses of two scenarios and relative change between two scenarios (black line with error bar, ±1SE) over the year.