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Profitability potential for *Pinus taeda* L. (loblolly pine) short-rotation bioenergy plantings in the southern USA

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ABSTRACT

The use of renewable resources is important to the developing bioenergy economy and short rotation woody crops (SRWC) are key renewable feedstocks. A necessary step in advancing SRWC is defining regions suitable for SRWC commercial activities and assessing the relative economic viability among suitable regions. The goal of this study was to assess the potential profitability, based on obtainable yield and economic feasibility; of *Pinus taeda* L. (loblolly pine) across 13 states of the southern USA. A process-based growth model, 3PG, produced estimated yields of *P. taeda* in terms of mean annual increment (MAI) that were evaluated as internal rate of return on investment (IRR) and land expectation value (LEV). Coastal areas (southeast Texas, southwest Louisiana, and northern Florida) have the highest potential MAI production ranging from 13.7 to 18.9 Mg ha^{-1} yr^{-1}. LEVs ranged from − 1126 to 3111 \$ ha^{-1} on upland sites and − 2261 to 2341 \$ ha^{-1} on lowland sites. IRR ranged from − 0.3% to 14.2% on uplands and − 2.9% to 10.4% on lowlands. On soils of the same textural class, LEV and IRR were higher on uplands relative to lowlands given lower site preparation costs, although the projected yield from upland soils are generally lower than those from lowland soils. The highest LEV and IRR were in northern Florida, southern Alabama, southern Georgia, and southern South Carolina. The lowest LEV and IRR were in Virginia and northern North Carolina. Spatially categorizing suitable lands in biological and economic terms can use geographic information system technology to advantage in combination with societal considerations to begin to answer sustainability questions as well as identify suitable sites for bioenergy plantations.

1. Introduction

Global energy production and use currently faces a major shift in focus from reliance on fuels derived from fossilized, carbon-rich sources to a mixture of renewable and non-renewable energy sources (Hoffert et al., 2002; Johnson et al., 2007). The advantages of petroleum sources include high energy content (42–45 GJ Mg^{-1}), relative geographic concentration, and ease of processing into transportation fuels. Yet increasingly these advantages are offset by approaching limits on a finite resource supply, political instability in areas of major reserves (Johnson et al., 2007), and the contribution of fossil fuel combustion to increasing atmospheric concentrations of greenhouse gases (GHG) that contribute to altering global climate (Edenhofer et al., 2011; IPCC, 2007). Renewable energy sources include those derived from plant material (biomass), either for direct combustion (e.g., fuelwood) or conversion to transportation fuels (e.g., ethanol or biodiesel).

Globally, almost 50% of roundwood harvested annually is used for fuel (FAO, 2005) in traditional use. This accounts for over 11% of yearly fuel consumption (Goldemberg and Coelho, 2004). Transportation fuels derived from sugar cane (*Saccharum officinarum*), corn (*Zea maize*), soybean (*Glycine max*), and oil palm (*Arecaceae elaeis*) are produced commercially but may compete with food crops for land (Runge and Senauer, 2007; Tilman et al., 2009). The future demand for bioenergy may be 10 times as large as present uses (Berndes, 2002) and most of this increase may come from woody crops (Berndes et al., 2003). The goal in the European Union, for example, is for biofuels to

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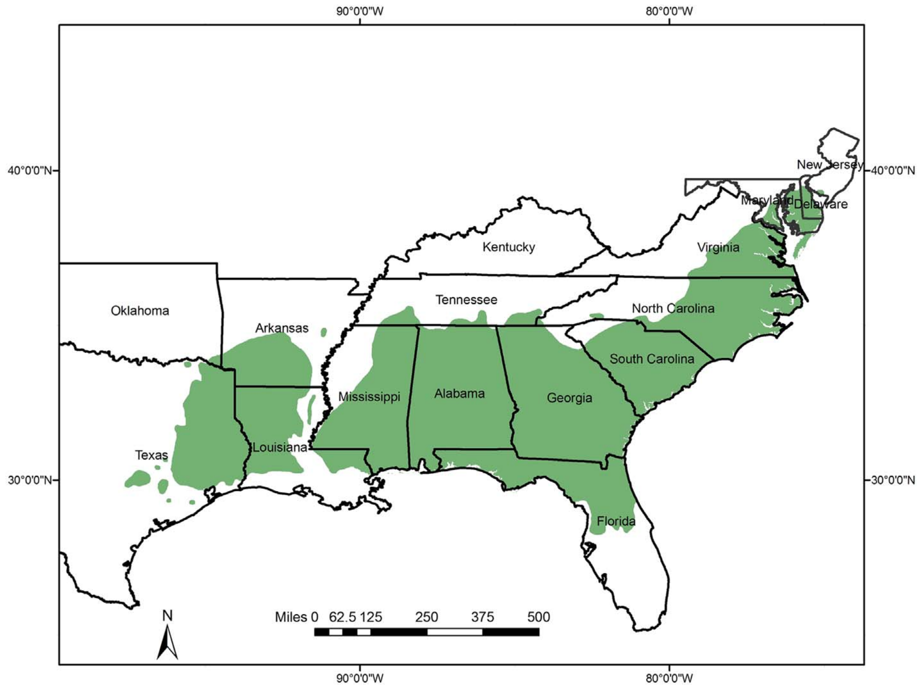

Fig. 1. *Pinus taeda* L. range.
Source: USGS Digital Representations of Tree Species Range Maps, available at http://esp.cr.usgs.gov/data/little/.

account for up to 10% by 2020, with renewables making up 30% overall. In the US, the planning target set by the Federal Biomass Research and Development Technical Advisory Committee is 30% replacement of current US petroleum consumption with biofuels by 2030 (Perlack et al., 2011, 2005).

If these goals are achieved, we may in a few years look back on the 20th Century, particularly the latter half, as the Fossil Fuel Anomaly. Nevertheless, a return to a bio-based economy will not be free of costs and will require that difficult choices be made between policies that produce different social benefits (e.g., Dauvergne and Neville, 2010; Kirschbaum, 2003; Righelato and Spracklen, 2007). Policy flexibility will be necessary as research provides new technology (Klass, 2003; Naik et al., 2010). All policy options will be challenged to demonstrate that they result in sustainable energy production at acceptable environmental costs (Gelfand et al., 2013; Robledo-Abad et al., 2017). Already there is resistance in Europe to biodiesel produced from palm oil and soybeans that have caused conversion of tropical forests (Koh and Wilcove, 2008) or in the US where cereal-based biofuels are thought to be in competition with food crops (Runge and Senauer, 2007; Tilman et al., 2009).

Concerns for food security and environmental quality have supported a shift away from oil palm and cereal grains toward second-generation biofuels derived from lignocellulosic or woody biomass, including agricultural and forest residues and dedicated woody crops (Perlack et al., 2005). The use of renewable biomass can help diversify markets for agriculture and forestry, create jobs, and promote rural development (Openshaw, 2010; Perez-Verdin et al., 2009). Concerns have been raised, however, about the sustainability of SRWC biofuels. Questions include whether bioenergy is net energy efficient and relatedly, is it carbon neutral; will it compete for land with crop production resulting in adverse effects on food security; and what effects will it have on biodiversity and provision of environmental services? There are no simple answers to these questions and in general, definitive answers require considering specific technology applied at a specific location. In order to address questions of sustainability, a necessary first step is to identify where dedicated SRWC plantations would be viable in terms of biological productivity and economic attractiveness. Spatially categorizing suitable lands in biological and economic terms can use geographic information system (GIS) technology to advantage in combination with societal considerations to begin to answer sustainability questions as well as identify suitable sites for bioenergy plantations.

Short-rotation woody crops (SRWC) are considered an important part of the bioenergy solution (Hinchee et al., 2009) in the Southeastern US where plantation forestry is economical (Stanturf et al., 2003a, b). Short-rotation woody crops are expected to account for over 27% of the total biomass resource potential (Perlack et al., 2005). Short-rotation woody crops are ideal renewable feedstocks because they can be strategically located near conversion facilities and provide ecological services, conserve soil and water, recycle nutrients, and sequester carbon (Coleman and Stanturf, 2006; Simpson et al., 2009; Zalesny et al., 2016).

Suitability must be assessed for individual species because their site adaptations and growth requirements differ. *Pinus taeda* L. (loblolly pine) is the predominant species for roundwood production in plantations in the southern US because it has the fastest early growth of the southern pines and is the most responsive to amendments (Zalesny et al., 2011). Although there is little published information on using loblolly pine for SRWC, it has been suggested as a candidate for SRWC bioenergy plantations (Kline and Coleman, 2010). The goal of this study was to assess the potential profitability, based on obtainable yield and economic feasibility, of *P. taeda* locally across 13 states of the southern US. This may be helpful for sustainability assessments as well as a useful coarse filter for siting bioenergy projects, by comparing feedstock potential based on biomass yield, land expectation value (LEV), and internal rate of return (IRR).

We modeled biomass growth potential of *P. taeda* using the process-based growth model 3PG, which stands for Physiological Principles Predicting Growth (Landsberg and Waring, 1997). Using the modeled growth potential of mean annual increment (MAI), we evaluated profitability potential using standard economic analyses of Land Expectation Value (LEV) and Internal Rate of Return (IRR). To visualize the profitability potential spatially, we modeled and expressed our results at the 5-digit ZIP Code Tabulation Area level (ZCTA), which are generalized areal representations of United States Postal Service ZIP Code service areas. Demographic and other census data are collected and reported by ZCTAs, which are generally smaller than political subdivisions such as counties. Further, smoothed visualizations that remove arbitrary boundaries were produced by Kriging and are provided as output.

2. Methods

2.1. Species and site characteristics

The *P. taeda* range is well-defined (Fig. 1), extending from the Atlantic Ocean on the east to central Texas on the west. The northern extent of the range runs from Virginia westward across North Carolina, Tennessee, Arkansas, to the southeastern corner of Oklahoma. The southern boundary is the coast of the Gulf of Mexico; in peninsular Florida, the historical range ends near Ocala. *P. taeda* grows on soils in four physiographic provinces, the Atlantic and Gulf Coastal Plains, the Piedmont, and the Ridge and Valley.

P. taeda can grow on a wide range of different textured soils, from deep sands to heavy-textured clays. With fertility and water holding capacity varying across the range of soils; reported yields vary across the range as well. The soils of the Lower Coastal Plain are generally poorly drained and often inherently phosphorus (P) deficient where pH is generally low and acidic (e.g., Spodosols). A subsample of the soils in this zone is organic Histosols. The majority of the Lower Coastal Plain soils are often sandy, but the better-yielding soils may have deposited sands underlain with clay (e.g., Ultisols). Decomposition, mineralization, and leaching can be high in these sandy soils and nitrogen deficiency is common as well.

Inland, the soils of the Upper Coastal Plain have more slope and elevation and drainage ranges from excessively well to very poor. Soil texture is often sandy with clay content varying. Nitrogen (N) limitations are common. Farther inland, soils of the Piedmont region are heavier textured, often clay. These areas were intensively farmed and experienced substantial erosion from the 1700s to the 1900s (e.g., Trimble, 1974). Resulting losses of the A-horizon were fairly complete and organic matter content is now limited. Available N is generally the primary factor limiting growth in this region. Some Upper Coastal Plain soils in Arkansas and Louisiana have higher silt content. Across Alabama and Mississippi, the region of so-called Black Belt soils limit productivity of pines due to iron deficiency caused by high inherent pH.

Weather across the region is humid with adequate rainfall for growth of *P. taeda*, thus water is generally not considered to limit growth in most years. However, growing season deficits are common for limited periods of time and extended periods of even multi-year drought do occur. A zone along the Gulf Coast and extending up the eastern Atlantic seaboard is mediated some by the ocean's effect and experiences a greater amount and frequency of rainfall.Within this zone, growth benefits from slightly lower temperatures, increased cloudiness, and resulting decreased vapor pressure deficits (VPDs). In contrast, further inland the continental climatic effect builds during some summer periods of hot, dry heat; growing season rainfall may be limited and VPD can be more severe, causing decreased stomatal conductance. In the very northern part of the range, temperature decreases somewhat and VPD may decrease slightly again. In the westernmost portion of the range, the Western Gulf is more likely to experience extended droughts.

2.2. Growth model

The 3PG model is a generalized process-based model that estimates primary productivity for a species and then allocates that growth to various parts (roots, shoots, branches, and leaves).Key steps in 3PG modeling are initializing site conditions, specifying silvicultural regimes, and choosing output variables. Initialization includes latitude, soil texture class, fertility response, maximum and minimum available soil water, initial available soil water, establishment dates, planting density, and initial foliage, stem, and root biomass weight. The 3PG growth model allows the user to input various silvicultural variables and regimes including irrigation, fertilization, and thinning treatments. Values are also required that represent the genetics of the species, expected defoliation rates, and a ranking for competition from weeds. The user has the ability to control which outputs will be available following a simulation.

The 3PG model predicts growth for a species given the climate, environment, and growing site conditions. The 3PG model most often is used to model individual stands and has been used successfully to model *P. taeda* in Scotland County, North Carolina (Landsberg et al., 2001) and Waycross, Georgia (Bryars et al., 2013). We used the *P. taeda* parameter list from Bryars et al. (2013) with only one exception, that being a relatively minor change in the age at which the branch and bark fraction equals one; Bryars et al. (2013) used 15 and we used 4 because of the shorter rotation length. Their version of the 3PG model modified for loblolly pine produced accurate estimates of productivity with site specific parameters for soil type, fertility, weather, and planting density (Bryars et al., 2013). We used the 3PG model to develop growth potential expressed as mean annual increment (MAI) for each 5-digit ZCTA in the range.

2.2.1. Soil inputs

Across its range, *P. taeda* yields vary by soil series, site position and nutrient and water availability. In general, nutrient and water availability are controlled by soil texture. To simplify inputs into 3PG, we developed a matrix of soil and associated soil water availability and fertility based on sand, sandy loams, clay loams, and clay textural classes. The matrix was further divided to represent differences in soil drainage; upland soils are moderately well to exceptionally well-drained and lowland soils are somewhat poorly-, poorly-, and very poorly-drained. Spatial and tabular soils data were obtained from the USDA Natural Resources Conservation Service SSURGO database, which provides spatial and attribute data in common GIS-ready formats for approximately 3000 soil survey areas across the US (http://sdmdataaccess.nrcs.usda.gov/; last accessed July 12, 2015). Soil map units were combined by texture units and the dominant texture class was assigned to each 5-digit ZCTA using the US ZCTA boundary map (https://www.census.gov/geo/reference/zctas.html; last accessed 12 February 2016) and the spatial overlay feature of ArcGIS©. The soil texture with the largest area within a ZCTA was selected to represent the soil texture input for that ZCTA into the 3PG model. The spatial distribution of soil textural classes in the *P. taeda* range is shown in Fig. 2.

Soil fertility and water holding capacity affect pine plantation growth. To capture the range of pine productivity potential, a matrix of fertility and available soil water was created based on the eight combinations of texture class and site position (Table 1). The fertility rating is an index ranging from 0 to 1, where a fertility rating of “1” implies very high nutrient availability and “0” frames the low end of inherent fertility without the addition of fertilizers. The soil fertility rating is based largely on how soil texture and soil organic matter affect soil nitrogen (N) and secondarily phosphorous (P) supplying capacity and retention capacity. For example, upslope sands generally have 0.5% to 1.0% organic matter and would be expected to provide minimum available N. In contrast, lower slope sands with 6–8% organic matter content could supply more of the annual N requirements of rapidly growing trees. Available soil water is a function of soil texture and depth; maximum and minimum available soil water was specified for each combination of texture class and site position; measurement units were millimeters of water depth per meter of soil depth (Table 1).

2.2.2. Fertilization response

Most commercial *P. taeda* stands are fertilized (Fox et al., 2007) and the response depends on the inherent or manipulated level of soil fertility. For example, a similar rate of fertilizer applied to a stand of *P. taeda* on a fertile clay soil on a river terrace will produce a lower growth response than the same rate applied to a stand on infertile sands. The

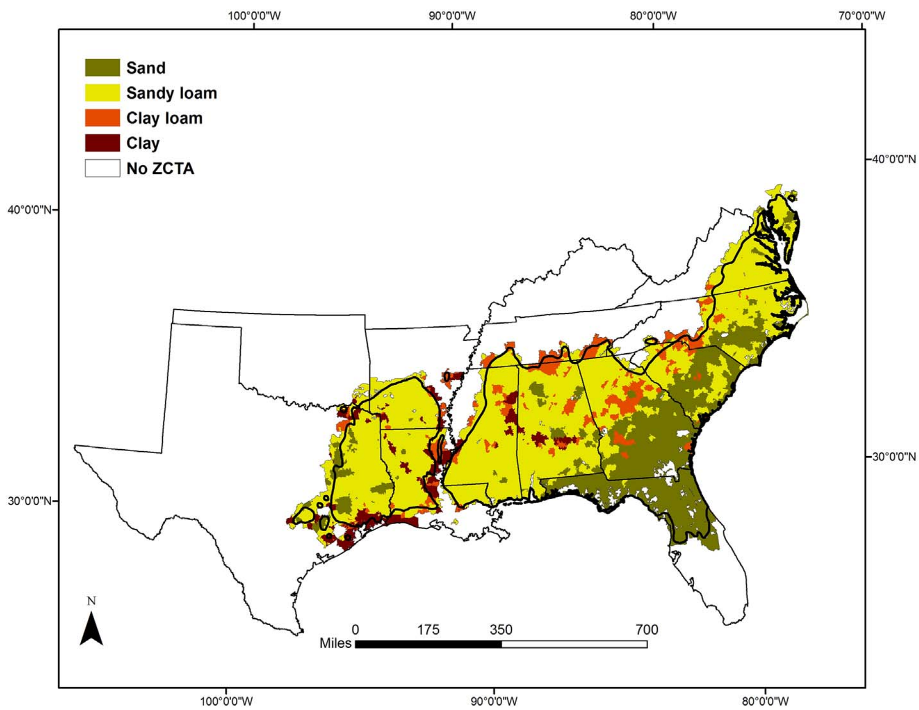

Fig. 2. Generalized soil texture. Soil textures in the four generalized classes used in the modeling for the 13 states in the southern US, displayed by Zip code tabulation area (ZCTA). Dark lines encompass the native range of *P. taeda*.

Table 1
Values for soil fertility rating, fertilizer response, and available soil water by soil texture, and site position for *Pinus taeda* (loblolly pine) used as input to the 3PG growth model.

Soil texture	Site position	Fertility rating[a]	Fertilizer response[b]	Minimum available soil water[c]	Maximum available soil water[c]
Sand	Upland	0.15	0.60	50	100
Sand	Lowland	0.30	0.45	50	100
Sandy loam	Upland	0.30	0.50	100	150
Sandy loam	Lowland	0.50	0.30	100	150
Clay loam	Upland	0.55	0.25	150	200
Clay loam	Lowland	0.70	0.10	150	200
Clay	Upland	0.65	0.15	200	250
Clay	Lowland	0.75	0.05	200	250

[a] Fertility rating scaled from 0 to 1; higher number represents greater inherent fertility.
[b] Fertilizer response rating scaled from 0 to 1; higher number represents a greater growth response to added nutrients.
[c] Available soil water is expressed as mm of available water per meter of soil depth.

basic principle behind this is one of decreasing growth response across soil types due to the inability to produce more leaf area for light interception on high fertility soils, because the high nutrient levels have already moved the leaf area to a higher level (Fox et al., 2007). Fertilizer response is included in the soil matrix used for the 3PG model (Table 1).

2.2.3. Climatic inputs

Weather data required to run the model included precipitation, minimum temperature, maximum temperature, and frost days. Monthly average data from individual weather stations was obtained from the NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html; last accessed July 12, 2015). Monthly averaged solar radiation at each weather station location was obtained from NASA Atmospheric Science Data Center (http://eosweb.larc.nasa.gov; last accessed July 12, 2015). For example, there were 169 weather stations in the state of Alabama but not all stations had complete data for the 10-year interval used to compute averages (1995–2004). Stations with incomplete records were excluded, leaving 93 weather stations covering 58 of the 69 counties in Alabama. For the nine counties with no data, we associated each one with the closest weather station with complete data.

Weather data were collected at stations; hence there were multiple data points within a ZCTA. We derived monthly ZCTA-level weather data by averaging monthly data from each weather station within a ZCTA over the 10-year period from 1995 to 2004. The data input for a given month was the average of 10 monthly values for any given weather variable.

2.2.4. Planting density

Conventional planting densities for pulpwood were maintained at 1795 seedlings ha^{-1} through the early 1990s. Subsequent decreases in average density have occurred since that time as seedling quality, seedling to sawtimber potential, and growth potential have improved. Currently many landowners plant 989 to 1606 seedlings ha^{-1}. Decreases in sawtimber stumpage and increases in pulpwood stumpage since 2006, along with increasing pellet production (Dale et al., 2017), have spurred interest in higher densities.

For SRWC, higher-density plantings of *P. taeda* are reasonable. Perhaps the best data available supporting higher densities are from the "Culture Density Studies" conducted by Plantation Modeling Research Cooperative at the University of Georgia. Plots were established throughout the Piedmont and Upper and Lower Coastal Plain regions of the Atlantic Coast Region. A similar study was conducted in the Western Gulf Coast region. Yield characteristics were evaluated at densities of 741, 1483, 2224, 2965, 3706, and 4448 planted trees ha^{-1} with two levels of intensive culture. Generally, yields increased little over 2224 trees ha^{-1}(Zhao et al., 2011). For the purpose of our modeling, a planting rate of 2224 trees ha^{-1} was used as to estimate biomass production.

2.2.5. Silvicultural regime

Our modeling assumed that the most appropriate and easily available planting stock for each site was used. Similarly, operationally intensive but economically feasible management regimes were included. Current fertilization prescriptions were used but irrigation was deemed too costly for SRWC. In any case, across the range for *P. taeda*, water is not a limiting factor except in years of extreme deficit. Because *P. taeda* does not readily sprout, coppicing was not included. A rotation length of 12 yr was used on all sites so that results were comparable across the region.

2.2.6. Planting stock

P. taeda seedlings currently available are all improved seed source material. Growers can purchase seedlings at one of three levels of genetic improvement: open-pollinated families, control-mass-pollinated crosses, or varietal lines. Stock options include bare-root and container. Genetic improvement has taken place through university-based cooperatives at North Carolina State (NCSU) and at Texas A & M (TAMU) Universities, as well as through individual efforts at industrial, state-funded orchards and nursery systems. Sub-lines of improved material for the Coastal Plain and Piedmont provinces have generally been kept separate. Regionalization has been historically maintained with the TAMU-based Western Gulf Cooperative using local material obtained west of the Mississippi River and the NCSU-based Forest Tree Improvement Cooperative using material from sources east of the Mississippi River. The NCSU program has completed three cycles of tree improvement; the TAMU program has completed two improvement cycles.

2.2.7. Fertilization

Research conducted by industrial forest growers, university scientists, and university-based cooperatives suggest that 224 kg ha^{-1} N and 22 kg ha^{-1} P provide increased yields for a four-to-eight year response period (Fox et al., 2007). We included treatments at these rate at ages 3 yr and 8 yr, to hold nutrient availability high throughout the 12 yr modeled rotation.

2.3. Economic model

Economic models for land expectation value (LEV) and internal rate of return (IRR) were implemented using Microsoft Excel to evaluate and compare the potential profitability of planting *P. taeda* across the range. Various approaches have been used to assess the cost structure and financial feasibility of SRWCs (El Kasmioui and Ceulemans, 2012). The most commonly used financial valuation method, net present value (NPV), discounts all costs and benefits over a rotation or a planning horizon to a reference time; it is the present value of future revenues minus the present value of future costs. The LEV is the NPV of bare land assuming an infinite series of identical even-aged forest rotations, starting from initially bare land. This approach correctly considers the opportunity cost of capital and land but includes neither non-market ecosystem services nor alternative uses such as urban development. The LEV has long been used for determining optimal forest management practices (Chang, 1998). The IRR of an investment is the discount rate at which the present value of costs equals the present value of revenues, i.e., the NPV equals zero.

We focused on biomass production (the cultivation phase), omitting the utilization phase that would require specifying processing destinations in order to include harvesting and transportation costs. Model inputs include the biomass production by ZCTA (MAI from the 3PG model) and biomass stumpage price. The modeled MAI is the volume inside bark (m^3 ha^{-1} yr^{-1}). Volume yield was converted to biomass using conversion factors for moisture content (50%) and volume to dry weight (500 kg m^{-3} dry) for *P. taeda*.

Costs for site preparation, planting, and fertilization (Dooley and Barlow, 2013) for soils on bottomlands and uplands were included (Table 2). The LEV was calculated for each ZCTA using an annual discount rate of 5% that includes a risk premium. Considering that the yield given by the model is inside-bark volume, the stumpage price was assumed to be US\$10 Mg^{-1} (nominal price not adjusted for inflation), slightly higher than Timber-Mart South pulpwood prices, which are based on outside bark (http://www.timbermart-south.com/; accessed July 12, 2015). The IRR was also calculated using the cash flow of costs and revenues of the total rotation. Mean values for MAI, LEV, and IRR

Table 2
Management practices and related costs for *Pinus taeda* (loblolly pine) on lowland and upland sites.

Year	Activity	Bottomland	Upland	Cost ($ ha^{-1})[a]
0	Chemical site preparation	X	X	185
0	Spot pile, shear, and bed	X		593
0	Di-ammonium phosphate application (22.4 kg ha^{-1})	X	X	89
0	Open pollinated seedlings (2224 ha^{-1})	X	X	124
0	Planting labor	X	X	178
0	Herbaceous weed control treatment	X	X	111
3	Urea Fertilizer application (487.5 kg ha^{-1})	X	X	395
8	Urea Fertilizer application (487.5 kg ha^{-1})	X	X	395
12	Harvest	X	X	

[a] Source: (Dooley and Barlow, 2013).

for each of the eight site position/soil texture units were tested for statistically significant differences using the Tukey-Kramer test at $\alpha = 0.05$ level.

2.4. Visualization

All 3PG model yield output and economic model results were developed at the 5-digit ZIP Code Tabulation Area level (ZCTA), which are generalized areal representations of United States Postal Service ZIP Code service areas (https://www.census.gov/geo/reference/zctas.html; accessed 12 February 2016). Demographic and other census data are collected and reported by ZCTAs, which are generally smaller than political subdivisions such as counties. There were 10,016 ZCTAs in the 13-state study region, which corresponded to 10,016 biomass production potential units for analysis. The average area of ZCTAs in the 13-state region was equal to 20,900 ha. Two sets of maps were produced in this study; one set was based on the 5-digit ZCTAs and the second set used a spatial interpolation technique (*Simple Kriging*) to avoid the influence of political boundaries and illustrate the general spatial pattern for the 3PG yield output and economic model outputs. The Kriging method has been widely used in soil science and geology (Oliver and Webster, 1990); it minimizes the variance of the estimation errors, resulting in a marked smoothing effect.

3. Results and discussion

3.1. Productivity

P. taeda productivity estimates (MAI) from the 3PG model ranged from a low of 5.4 Mg ha^{-1} yr^{-1} on upland sand sites to a high of 20.4 Mg ha^{-1} yr^{-1} (Table 3). Most mean values of MAI were significantly different at the $\alpha = 0.05$ level. Generally, models are validated by using one set of data to parameterize the model and comparing model estimates to the observed or measured data from a second set of sites. Discrepancies to the modeled performance are then adjusted by changing the fertility rating or available soil water. For this study, validation was a comparison of the modeled output to the observed yields over the range of the species. These results compare well with literature values; for example Dickens et al. (2011) summarized the potential as 3.8 to 28.4 Mg ha^{-1} yr^{-1} (stemwood plus bark). Caputo and Volk (2011) summarized the productivity potential of *P. taeda* under intensive management (fertilized and/or irrigated) as 8.1 to 19.1 Mg ha^{-1} yr^{-1}. Wright (2010) provided a summary of verified pine yields from southern US studies; biomass ranged from 3.4 to 19.1 Mg ha^{-1} yr^{-1}. The highest experimental values came from sites near Waycross, Georgia that received weed control and fertilization throughout the study (Borders et al., 2004). Southeast Texas, southwest

Table 3
Projected *Pinus taeda* (loblolly pine) biomass yield MAI by soil texture and site position[a]. Levels not connected by same letter are significantly different (α = 0.05) using Tukey-Kramer test.

Site position	Texture	Yield ($Mg\ ha^{-1}\ yr^{-1}$)			
		Minimum	Maximum	Mean	
Lowland	Clay	8.3	20.4	13.2	A
Lowland	Clay loam	7.6	18.8	12.3	B
Upland	Clay	7.4	18.6	12.3	B
Upland	Clay loam	6.9	18	11.9	C
Lowland	Sandy loam	6.7	17.5	11.4	D
Upland	Sandy loam	6.1	16.4	10.8	E
Lowland	Sand	6	16.4	10.5	E
Upland	Sand	5.4	15.5	9.9	F

[a] Operationally intensive fertilization and planting density of 2224 trees ha^{-1}.

Louisiana, and north Florida have the highest potential MAI production in the range of 25 $m^3\ ha^{-1}\ yr^{-1}$ to 34.6 $m^3\ ha^{-1}\ yr^{-1}$ (Figs. 3 and 4), corresponding with Coastal Plain sites. The lowest potential MAI production was in the most northerly part of the range, in south Virginia and most of North Carolina (12 to 20 $m^3\ ha^{-1}\ yr^{-1}$).

The underlying principle of the 3PG model and the ability to fine tune parameters for a given species allows it to be used successfully for modeling production on a variety of sites and environmental conditions (Landsberg et al., 2003). Almeida et al. (2004) found that the model could be used to accurately predict the potential for a species in situations where the species had not previously been planted. The 3PG model has been used to simulate growth for stands of loblolly pine to compare different treatments (Bryars et al., 2013; Landsberg et al., 2001). It has been used to predict growth for *Picea abies* in Europe (Waring, 2000), *Pinus radiata* in Australia (Coops et al., 1998), *Pinus patula* in Swaziland (Dye et al., 2004), *Eucalyptus gobulus* in Australia (Sands and Landsberg, 2002), *Eucalyptus grandis* and hybrids in Australia, South Africa (Dye et al., 2004) and Brazil (Almeida et al., 2004). It has also been used to model growth of hybrid poplar, *Populus* spp. (Amichev et al., 2010) and *Salix* spp. in Canada (Amichev et al., 2011) and the US (Hart et al., 2015; Headlee et al., 2013; Zalesny et al., 2012). Even though the 3PG model could be used to predict biomass production fairly well, the accuracy of the model was limited by the simplified leaf area dynamics and site fertility differences. Bryars et al. (2013) noted that adjusting the fertility ratings improved estimates of biomass production for *P. taeda*. Alternatively, Subedi et al. (2015) used site index values (base age 25 yr) for *P. taeda* plantations to estimate the fertility rating as a fixed parameter. The 3PG model explained 89% of the variation in yield using the fertility rating derived from site index values for soil series in the SSURGO database (Subedi et al., 2015). Application of this approach to SRWC rotation lengths has not been tested.

Our projected yields should be interpreted with caution for individual sites within the region as site and even micro-site effects may be significant. The 3PG model incorporates weather data, soil and fertility data, and species specific parameters to estimate potential volume production and we used simplified soils inputs and mean monthly weather data over a specific 10-year period. Using more detailed soils or current weather data and changing the fertility ratings could produce different results. Available soil water is not considered a major limitation to growth for *P. taeda* in most areas of the southern US. In the case of the weather data, we sought to capture the differences in site productivity for a region but this method ignores weather extremes. Over a longer rotation, the good, average, and poor years of biomass production even out but over the life of a SRWC, a few extreme years could dramatically change the modeled or realized productivity. Mean annual precipitation generally ranges from 100 to 132 cm but some years may have deficits of 25 to 64 cm, substantially limiting growth in comparison to average precipitation years. The flexibility of the 3PG model allows for different climate scenarios to be developed and risk of failure or lowered yields from extreme events such as drought to be assessed.

3.2. Potential productivity

Estimated land expectation (LEV) values ranged from − 1126 $ ha^{-1} to 3112 $ US ha^{-1} on uplands and − 2263 $ ha^{-1} to 2342 $ ha^{-1} on lowlands (Table 4). All mean values of LEV were significantly different at the α = 0.05 level. Estimated IRR ranges from − 0.3% to 14.2% on uplands and − 2.9% to 10.4% on lowlands (Table 5). Most mean values of IRR were significantly different at the α = 0.05 level. For the same soil texture, LEV and IRR are higher on

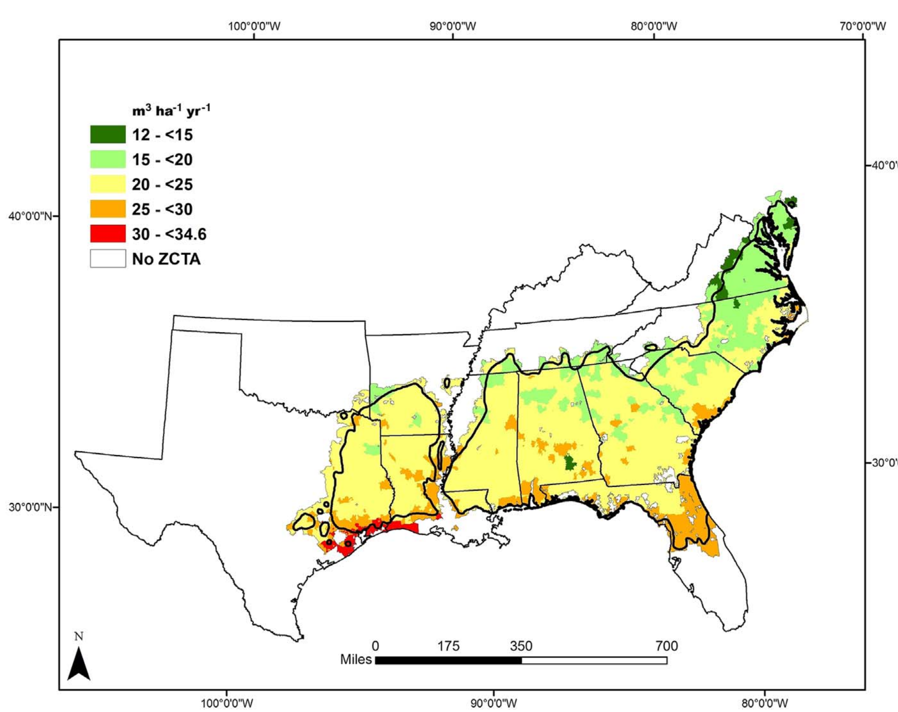

Fig. 3. Loblolly pine yield by ZCTA. Mean annual increment (MAI) of *Pinus taeda* inside bark wood volume ($m^3\ ha^{-1}\ yr^{-1}$) at age 12 for the 13 states in the southern US, modeled using 3PG and displayed by Zip code tabulation area (ZCTA). Dark lines encompass the native range of *P. taeda*.

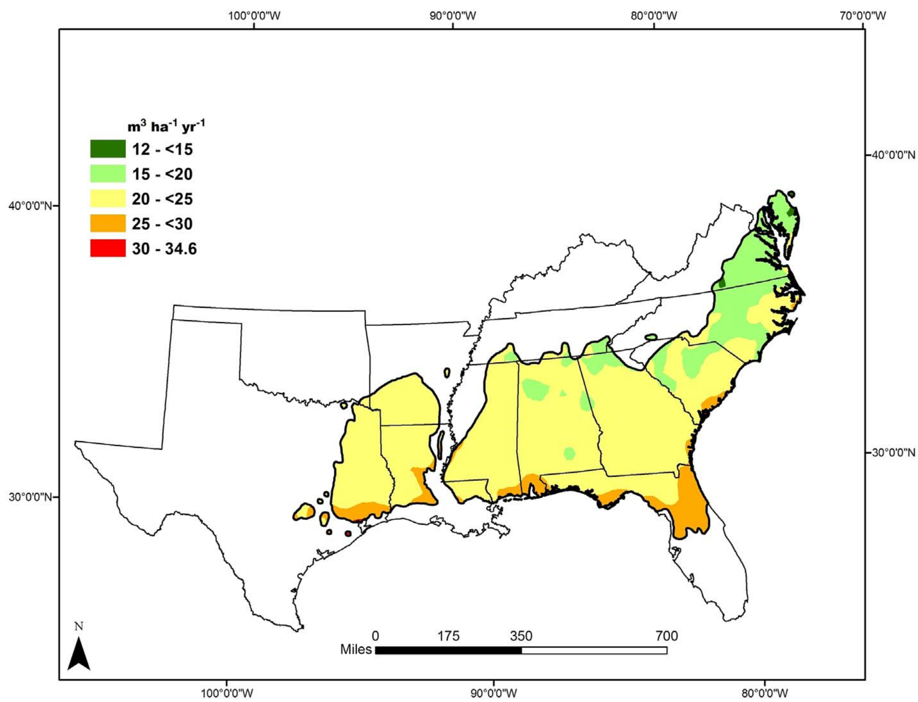

Fig. 4. Loblolly pine yield smoothed by Kriging. Mean annual increment (MAI) of *Pinus taeda* inside bark wood volume ($m^3\ ha^{-1}\ yr^{-1}$) at age 12 for the 13 states in the southern US, modeled using 3PG; visualization smoothed using simple Kriging. Dark lines encompass the native range of *P. taeda*.

Table 4
Estimated LEV for *Pinus taeda* (loblolly pine) by soil texture and site position. Levels not connected by same letter are significantly different (α = 0.05) using Tukey-Kramer test.

Site position	Texture	LEV ($ ha^{-1})			
		Minimum	Maximum	Mean	
Upland	Clay	− 480.98	3113.98	1072.55	A
Upland	Clay loam	− 600.46	2923.15	938.28	B
Lowland	Sand	− 2262.79	1046.44	778.45	C
Upland	Sandy loam	− 934.01	2395.78	555.85	D
Lowland	Sandy loam	− 2010.06	1459.57	482.79	E
Upland	Sand	− 1125.75	2079.39	323.59	F
Lowland	Clay loam	− 1746.31	1879	186.68	G
Lowland	Clay	− 1551.78	2342.62	58.98	H

Table 5
Estimated IRR for *Pinus taeda* (loblolly pine) by soil texture and site position. Levels not connected by same letter are significantly different (α = 0.05) using Tukey-Kramer test.

Slope position	Texture	IRR (%)				
		Minimum	Maximum	Mean	Range	
Upland	Clay	3.3	14.2	9.1	8.9	A
Upland	Clay loam	2.7	13.8	8.7	11.1	B
Upland	Sandy loam	0.9	12.6	7.4	13.5	C
Upland	Sand	− 0.3	11.9	6.6	12.2	D
Lowland	Clay	0.5	10.4	5.6	9.9	E
Lowland	Clay loam	− 0.3	9.6	4.9	9.9	E
Lowland	Sandy loam	− 1.6	8.8	4.1	10.4	F
Lowland	Sand	− 2.9	8	3.1	10.9	G

uplands than on lowlands because of lower site preparation costs, although the projected yield of upland soils are generally lower than those of lowland soils.Spatially, the highest estimated LEV is in north Florida, and gradually decreases in the region of southern Alabama, southern Georgia and southern South Carolina until reaching the lowest LEV in the Piedmont of Virginia and northern North Carolina (Fig. 5). The IRR spatial trend is similar pattern to LEV for *P. taeda* (Fig. 6).

Yields as measured in MAI were higher in the southern portion of the ranges and along the southeast coastal regions of the US. Higher yields in the southern portion of the operable ranges also resulted in corresponding higher estimates of LEV and IRR. Return on invested capital was competitive, dependent on the location of SRWC in its operable range. *P. taeda* had attractive IRR of approximately 4% on uplands and approximately 10% on lowlands. The yield results can be used for further economic evaluation, carbon sequestration, and sustainability research.

3.3. Silvicultural options

The silvicultural regime used in the model represents current and emerging practice; however, many feasible management regimes and site adaptations have been proposed. Within a single soil series, there can be a wide range of texture mixes; even with similar textures, soil depth and organic matter content can vary greatly and there may be interactions between genetics and environmental conditions where certain genotypes are better adapted to a given site, although there is little evidence for genotype by environment interactions in loblolly pine (McKeand et al., 2006; Roth et al., 2007). Nevertheless, access to elite genotypes is another factor that may increase one firm's competitive advantage over another. The well-developed value chain for loblolly pine in the southern US provides opportunities for diverse silvicultural systems that could incorporate a biomass/bioenergy component, in addition to dedicated SRWC plantations (Zalesny et al., 2011). For example, Albaugh et al. (2012) examined interplanting switchgrass (*Panicum virgatum*) as a bioenergy crop in a loblolly pine sawlog plantation. The switchgrass, along with residues from harvesting the pine could be used for bioenergy and interplanting the switchgrass within a pine plantation was less risky than a pure switchgrass planting for a relatively new biofuel market (Albaugh et al., 2012; Haile et al., 2016). Conceivably, the pine overstory could be managed for pulpwood or pellet production along with a switchgrass understory. Koch (1980) conceptualized a dual-cropping system for loblolly pine where a pine bioenergy crop was direct-seeded under a planted sawlog stand. Scott and Tiarks (2008) reported on such as system after 22 years; as long as the direct-seeded pines were harvested within 5 yrs., there was no deleterious effect on the overstory pines. More recently, the FlexStand system proposed by Arborgen is another version of dual-cropping that involves planting an elite genotype for the crop tree and an improved

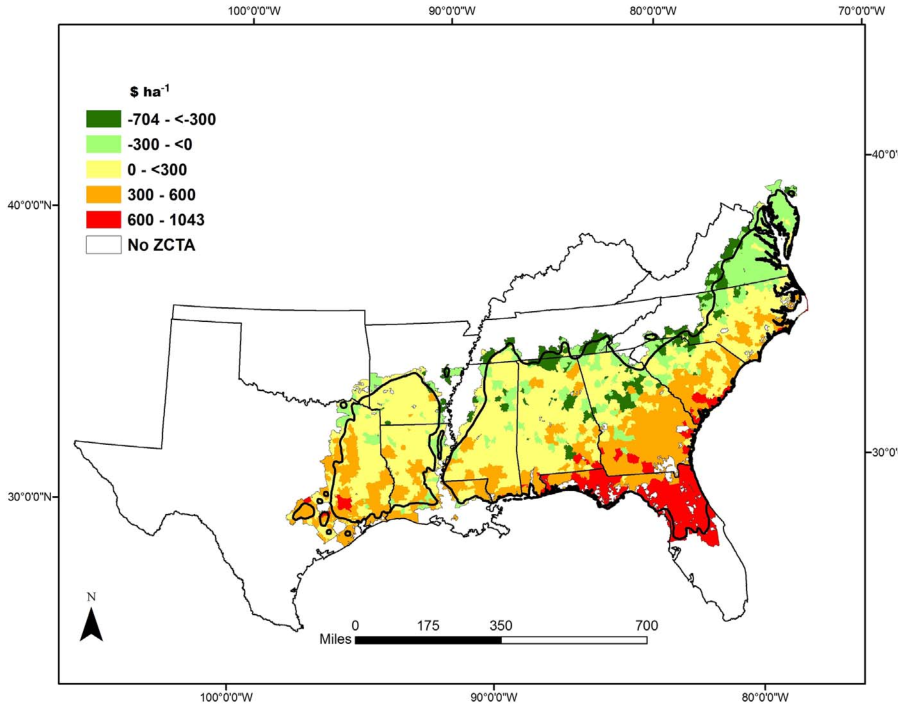

Fig. 5. Land expectation value. Land expectation value (LEV) for *Pinus taeda* inside bark wood volume ($m^3\ ha^{-1}\ yr^{-1}$) for a 12-yr rotation, expressed in $\$\ ha^{-1}$ and displayed by Zip code tabulation area (ZCTA). Dark lines encompass the native range of *P. taeda*.

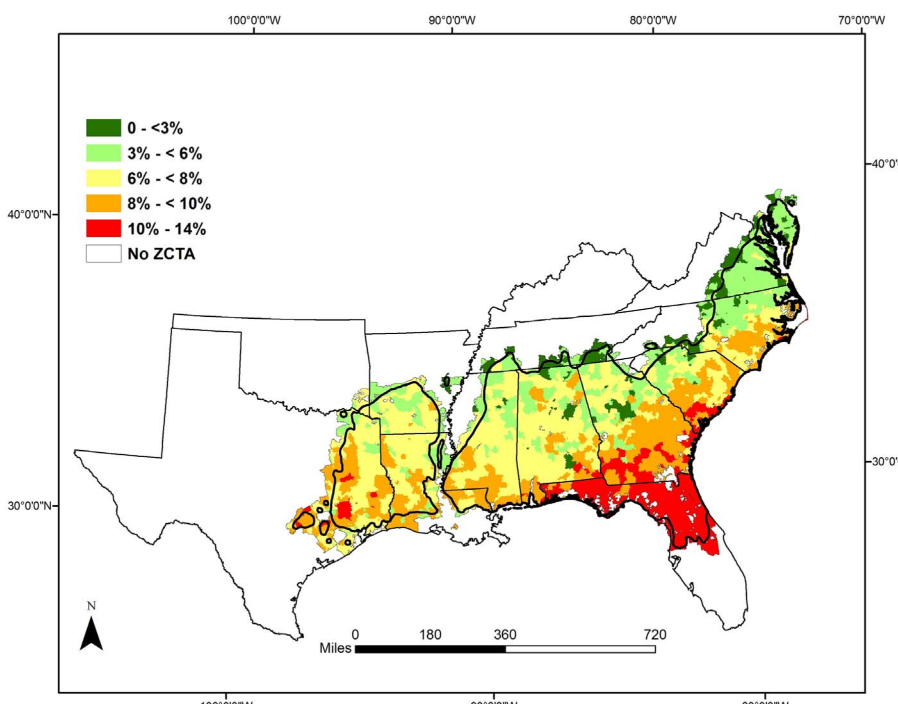

Fig. 6. Internal rate of return. Internal rate of return (IRR) for *Pinus taeda* inside bark wood volume ($m^3\ ha^{-1}\ yr^{-1}$) for a 12-yr rotation, expressed as percentage and displayed by Zip code tabulation area (ZCTA). Dark lines encompass the native range of *P. taeda*.

but less expensive seedling for biomass (Amateis and Burkhart, 2012). These systems are being studied but as yet, optimal spacing, harvesting, and economics of these systems are undetermined (Zalesny et al., 2011).

4. Conclusions

The production of woody biomass from purpose-grown, short rotation woody crops can meet the need to insure long-term, accessible and sustainable feedstock for emerging biomass energy production facilities or for pellet exports. Estimating the productivity potential of a species across a region is best done using a physiologically-based model that integrates the inherent physical properties of a species with the soil and climate data to predict expected biomass production. The 3PG model can be a powerful planning tool for estimating yield by species and by region. The model has been shown to reliably predict growth in several species of trees in varied environmental conditions. The combination of the 3PG growth model and economic analysis showed that in the southern US, attractive LEV and IRR values are obtained only when biomass productivity is above threshold values that are determined by ecosystem characteristics. Using currently available seedling material and silvicultural systems, *P. taeda* SRWC yielded IRR of approximately 4% on uplands and approximately 10% on lowlands in the southern US. The model could be used as well to evaluate different silvicultural combinations. For example, we described some emerging intercropping and dual-cropping systems under development that could be incorporated into the model and evaluated with our approach.

Our results, displayed spatially at the scale of 5-digit ZCTAs, indicated regions of potentially high profitability for *P. taeda* SRWC that can guide more detailed, site-specific assessments of utilization and processing facilities. More detailed assessments could use our results as a coarse filter to look either at where to locate a dedicated bioenergy facility or to evaluate the potential for a developed site to utilize *P. taeda* to produce bioenergy. At the landscape-scale, however, there is insufficient empirical data to evaluate all combinations of site, climate, and management systems; the 3PG model also can be used to compare several potential species for bioenergy production in the region. This would require modifying the 3PG model for each species and comparing biomass yields and economic criteria under comparable conditions. Another use would be in various future scenarios to project how different climate conditions may alter the array of potentially profitable sites and management combinations and the risk of economic losses posed by the likelihood of extreme events such as multi-year drought. A further use would be in combination with regional timber models, such that potential increased supply from SRWC would be used to assess the effects on price and pulpwood markets under different scenarios of demand that was influenced by policy options and incentives for renewable energy supplies.

In addition to evaluating potential profitability of different silvicultural systems, our findings could be used to evaluate different policy options, in particular aspects of sustainability and carbon benefits. Our results indicate the most likely areas in the region to locate bioenergy plants using *P. taeda*; these results could be coupled with siting programs to simulate the most likely locations for conversion facilities and then assess potential effects such as competition for land with food crops or commercial timber production; effects on biodiversity and water resources; or sustainability under future climate. Biomass yield predictions from the model can be converted to carbon and used to evaluate sequestration potential from SRWC plantations established on former agricultural land.

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