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Potential Profitability Zones for *Populus* spp. Biomass Plantings in the Eastern United States

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Short rotation woody crops (SRWCs) are key renewable feedstocks for the emerging bioeconomy. A critical step in developing a bioeconomy is defining suitable regions for commercial SRWC activities. The goal of this study was to estimate the obtainable yield in mean annual increment and economic returns on investment for *Populus deltoides* and *Populus* hybrids for the 33 eastern states using the 3PG model (Physiological Principles Predicting Growth). Yields ranged from 0.5 to 11.9 oven-dry tons (ODT) $ac^{-1}yr^{-1}$ with a mean of 3.9 ODT $ac^{-1}yr^{-1}$. Spatially, southern Illinois, Louisiana, Indiana, and central Missouri have the highest yield production. Kentucky, Tennessee, North Carolina, Oklahoma, Arkansas, and Virginia, as well as other southern regions of Georgia, Alabama, Mississippi, and South Carolina, have the lowest potential yield production. Land expectation values of *P. deltoides* ranged from –$1,369.12 to $1556.14/ac. The median internal rate of return (IRR) for the northern states was 2.0%, with a range of −13.9% to 14.6%. Spatially explicit potential profitability zones are useful as a coarse filter for evaluating sites for bioenergy projects that are under construction, in operation, proposed, or where due diligence is required.

Keywords: short-rotation woody crops (SRWCs), 3PG (Physiological Principles Predicting Growth) models, SRWC economics, *Populus deltoides*, hybrid poplar

Interest in wood for energy and other products in the bioeconomy has rekindled research on short rotation woody crops (SRWCs; Hinchee et al. 2009). Until fossil fuels were widely adopted for residential and industrial uses in the 1800s, wood fueled most of the energy consumption in the United States (Mendel and Lang 2012) and still accounted for 21% of energy consumption in 1900 (US Energy Information Administration 2011). 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). Nevertheless, renewable biomass only accounted for approximately 5% of total energy consumption in 2009 (US Energy Information Administration 2011). Projections of a total biomass resource potential of 1.37 billion oven-dry tons (ODT; Perlack et al. 2011) are mostly forest residuals and agricultural biomass, but SRWCs, in dedicated plantations, are expected to account for 377 million ODT. SRWCs and other biomass crops are ideal renewable feedstocks because they can be strategically located near conversion facilities, thereby reducing transportation costs. An advantage over annual biomass crops such as maize is that SRWCs can be "stored green on the stump" and continue to grow until needed (Zalesny et al. 2011, 2016a). Properly designed and managed SRWCs also will provide ecological services, conserve soil and water, recycle nutrients, and sequester carbon (Coleman and Stanturf 2006, Zalesny et al. 2016b).

Identifying suitable lands and economic achievability for SRWCs in a spatial context is required for this important renewable biomass resource. Geographic information system (GIS) technology, combined with growth and yield information and economic analyses, can be used to advantage for spatially defining the suitability of land by integrating biological, economic, and societal factors with information on soils, geology, vegetation, current land uses, and topography (Perdue et al. 2011, Perlack et al. 1992, Zalesny et al. 2012).

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Suitability depends on the SRWC species under consideration. Many species have been examined for SRWCs over the years (McAlpine et al. 1966, Steinbeck 1999), and hardwoods have been of particular interest because of their ability to sprout and be managed as coppice. *Populus* species, specifically *Populus deltoides* and hybrid poplars, have generated great interest because of their rapid early growth, ease of propagation, and ready hybridization (Stanturf and van Oosten 2014, Stanturf et al. 2001). *Populus* species are being considered for dedicated bioenergy plantings to meet US energy needs (Perlack et al. 2011, Vance et al. 2014).

The goal of this study was to assess the potential yield and economic feasibility of *Populus* species grown in dedicated SRWC plantations across 33 states of the eastern United States in terms of spatially defined potential profitability zones. *P. deltoides* Bartr. ex Marsh. var. *deltoides* is the fastest growing commercial species found among our native tree species (Cooper and Van Haverbeke 1990, Stanturf et al. 2001). The native range of *P. deltoides* (Eastern cottonwood) and *Populus* hybrids extends from southern Quebec, westward into North Dakota, south to central Texas, and east to northwestern Florida and Georgia (Cooper and Van Haverbeke 1990, Dickmann 2001). Cottonwood and hybrid poplars are absent from the higher elevations in the Appalachian Mountains and from much of Florida. Hybrid poplars occur naturally throughout the United States and Canada wherever compatible species ranges overlap (Demeritt 1990), and much research has been completed on quantifying and improving hybrid poplar production, including breeding programs incorporating non-native *Populus* species (Stanton et al. 2002, 2014).

We used the process-based growth model 3PG, which stands for Physiological Principles Predicting Growth (Landsberg and Waring 1997), to project the biomass growth potential of Eastern cottonwood in the southern states and hybrid poplar in the northern states. Potential profitability was evaluated using the modeled growth potential of mean annual increment (MAI) in $m^3\ ha^{-1}yr^{-1}$, inside bark, in terms of land expectation value (LEV) and internal rate of return (IRR). To visualize potential profitability, the results were expressed spatially at the five-digit zip code tabulation area (ZCTA) level and potential profitability zones were displayed using GIS techniques. ZCTAs are generalized areal representations of US Postal Service zip code service areas.[1] Demographic and other census data are collected and reported by ZCTAs, which are generally smaller than political subdivisions such as counties. Furthermore, smoothed visualizations that remove arbitrary boundaries were produced by kriging and are provided as another visualization of potential profitability zones.

Poplar species are particularly suited for SRWCs because they are fast growing, easily propagated vegetatively, and readily coppice (Stanturf et al. 2001). Properly sited SRWC plantations can attain annual yields of 4.5 ODT ac^{-1} (10 $Mgha^{-1}yr^{-1}$) on marginal sites and up to 9 ODT $ac^{-1}yr^{-1}$ (20 $Mgha^{-1}yr^{-1}$) on better sites (Stanturf et al. 2001, Zalesny et al. 2009). We evaluated the growth potential of Eastern cottonwood (*P. deltoides*) in SRWCs in the southern states and hybrid poplar in the northern states. The dividing line for the modeling segregation was considered to be the northern boundaries of the states of Arkansas, Kentucky, Virginia, and Maryland. Early studies showed that clones of the naturally occurring *P. deltoides* outperformed hybrid poplars in the South, largely because of greater disease resistance (Maisenhelder 1970).

The results of our growth and economic analyses may be helpful for bioenergy projects that are under construction or in operation, proposed, or where due diligence is required. Such information is necessary for any business venture when siting a biofeedstock conversion facility, and computer-assisted decision support systems are becoming available to aid in siting such plants (e.g., BioSAT; Perdue et al. 2011). Although several studies have examined siting bioenergy plantations of poplars and other species (Amichev et al. 2010, Aylott et al. 2008, Zalesny et al. 2012), none have attempted such analysis for the entire eastern United States. Information on the potential productivity of candidate feedstock species incorporated into decision support systems such as BioSAT (Perdue et al. 2011) could be useful as a coarse filter over a region to reduce the number of potential sites requiring more detailed analysis.

Methods

Species

Eastern cottonwood is wide ranging and, along with hybrid poplar, adapted to a wide range of weather conditions. Frost tolerance is high, except for late spring freezes that occur after growth initiation. The species tolerate temperatures ranging from as high as 115° F to as low as −49° F (Cooper and Van Haverbeke 1990). Where occurring naturally, *P. deltoides* is found primarily on alluvially enriched and periodically recharged, well-drained soils in floodplains of primary or secondary drainage systems (Cooper and Van Haverbeke 1990). The best cottonwood sites are on well-aerated soils that have sufficient moisture and nutrients. Sufficiently deep soils (>3 ft to the water table) that have a medium texture (sand/loam) and pH in the range of 5.0–7.5 are preferred (Baker and Broadfoot 1979). To a great extent, soil texture and drainage class determine the suitability of a site for poplar (Dickmann and Stuart 1983, Headlee et al. 2013, Stanturf et al. 2001). Soils with less than optimal conditions can be improved by ditching, installing drain tile, subsoiling, irrigation, fertilization, or some combination (Stanturf and van Oosten 2014). Eastern cottonwood can perform acceptably well on heavy clay soils as long as competing vegetation is adequately controlled (Stanturf et al. 2001). Hybrid poplars grow well on sandy loam to clay loam textured soils with good moisture availability (i.e., if soils are not excessively well drained but are deep without a hard pan and have a pH of 5.0–7.5, organic matter content in the range of 3–8%, and adequate nutrients; Zamora et al. 2011).

Poplars (both *P. deltoides* and hybrid *Populus*) are capable of producing high levels of leaf area (up to 6–8 leaf area index), resulting in high capacity for light interception and annual wood additions. Poplars are deciduous, and annually rebuilding and supporting these high levels of leaf area demand high levels of available soil nutrients. Good sites for poplars have inherently high soil fertility and cation exchange capacity with good drainage that allows unimpeded root exploration and nutrient uptake. Poplars grown in SRWC plantations usually require additions of fertilizer nutrients at planting and throughout the rotation to maintain optimal growth (Coleman et al. 2006, Isebrands 2007, Stanturf et al. 2001).

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 plant parts (roots, shoots, branches, and leaves). Solar radiation, temperature, and photosynthetic parameters specific to a species are combined with limiting factors including site fertility and water holding capacity to estimate productivity on a site. The model first estimates gross primary productivity as a function of absorbed photosynthetically active radiation and the species-specific effective canopy quantum efficiency (i.e., carbon produced per unit of light intercepted). Net primary productivity is estimated from a constant ratio of gross to net primary productivity.

The 3PG modeling structure consists of two types of equations or submodels: equations that estimate biomass monthly production values and others that allocate the biomass to various tree components. The model requires approximately 42 inputs to run; of these, some are constants or defaults for trees but some variables are species dependent. The primary variables in the model are detailed tree physiological measures, including canopy quantum efficiency, canopy conductance, root turnover, specific leaf area, and foliage weights to stem weight ratios (Table S1[S]). The values of these variables are likely specific to the clones being used (e.g., Headlee et al. 2013, Zalesny et al. 2012), and most work to date has used a combination of literature values and yield data from experimental treatments of fertilization, irrigation, or both to parameterize the model. We followed this approach and parameterized our model with the data available from multiple studies in which the parameter values of interest may or may not have been the focus of the study; some values that were specific for hybrid poplar were different for *P. deltoides* (see *P. deltoides* section).

The 3PG model can be used to predict growth for various SRWC species given specific climate, environmental, and growing site conditions (e.g., Headlee et al. 2013, Zalesny et al. 2012). Landsberg and colleagues (2003) concluded that the underlying principle of the model and the ability to fine-tune parameters for a given species allow it to be used successfully for modeling the production of multiple species for various sites and environmental conditions. Almeida and colleagues (2004) found that the model could be used to accurately predict the potential for a species in a greenfield situation in which the species had not previously been planted. The 3PG model has been used successfully to model growth of hybrid poplar in Canada (Amichev et al. 2010) and the northern United States (Headlee et al. 2013, Zalesny et al. 2012).

Hybrid Poplar

We used several parameters from Amichev and colleagues (2010) directly or as a base that was adjusted. Their study for hybrid poplar Walker (*P. deltoides* × *Populus nigra*) used data from three sites in Saskatchewan, which is at the northern extreme of our region (latitude 53–54° N). Because the study sites used by Amichev and colleagues (2010) were planted at comparatively low densities, using their values for canopy quantum efficiency, stem-foliage partitioning, and specific leaf area produced estimates lower for the northern United States than validated production numbers for hybrid poplar in the literature. Notwithstanding, we used values from Amichev and colleagues (2010) for specific gravity, temperature range, and the frost modifier. Parameter values from Amichev and colleagues (2010) that contrasted strongly with our values included maximum canopy quantum efficiency and their zero values for litterfall and root turnover as well as branch and bark fractions (Amichev et al. 2010). Our parameters also differed from those used by Headlee and colleagues (2013), who calibrated their 3PG model for a specific group of hybrid poplar clones (DN17, DN34, and DN182).

P. deltoides

Parameters used for *P. deltoides* in the southern states varied slightly from those used for hybrid poplar. The ratios of foliage:stem partitioning at two stem diameters, 0.8 and 8 in. (2 and 20 cm, PFS2 and PFS20, respectively), were 0.5 and 0.3, respectively, for hybrid poplar versus 0.6 and 0.4, respectively, for *P. deltoides*. Cerasoli and colleagues (2014) considered both possible physiological adjustments and growth responses to temperature and found no acclimation in photosynthesis, respiration, or stomatal conductance, implying that predicting expected yields at different mean temperatures would have to consider shifts in allocation. They concluded that broad correlations between biomass and mean temperature may be insufficient to accurately estimate plant growth. In our modeling runs we tried to define a temperature curve that would be an optimal growth regime for *Populus* for the different geographical area climates considered and for the plant material deployed. Thus, for the optimal temperature for growth we used 68° F (20° C) for hybrid poplar (Amichev et al. 2010) and 77° F (25° C) for *P. deltoides* (Drew and Chapman 1992).

The coefficient of conductance, which defines stomatal response to vapor pressure deficit, was set at 0.043 $mbar^{-1}$ for *P. deltoides* and 0.06 $mbar^{-1}$ for hybrid poplar, which average the 0.05 $mbar^{-1}$ that has been used in most 3PG modeling for *Populus* (Headlee et al. 2013, Will and Teskey 1997). Our rationale was that the more southern origin *P. deltoides* should be more drought adapted than the more northern hybrids. Another parameter, maximum tree size, also differed. Because we used different planting densities, the maximum stem size obtainable differed. The maximum stem size per tree was set at 485 lb $tree^{-1}$ for *P. deltoides* and at 221 lb $tree^{-1}$ for hybrid poplar.

Validation

The best practice for model validation is to completely parameterize a model on one set of data and then compare the modeled growth data to observed or measured data from a second set of data. Discrepancies to the modeled performance are then adjusted by site-specific parameters. For example, Headlee et al. (2013) adjusted the fertility rating and age at canopy closure and validated their model against previously published biomass data for the clones of interest (Netzer et al. 2002). Because our interest was in yields over the geographic range of the species and at the regional level, rather than comparing yields of different stands, our modeled outputs were compared to published or observed data for the region rather than values for a site.

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 schedules. Values are also required that represent the genetics of the species, expected defoliation rates, and a ranking for competition from weeds.

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/FS-2016-101R2.

Table 1. Soil fertility index ratings and maximum and minimum available soil water values (inch water/foot soil depth) for different soil texture and slope position combinations; limited to sites where poplars are adapted without supplemental irrigation.

Soil texture	Site position	Fertility rating	Minimum available soil water	Maximum available soil water
Sandy loam	Upland	0.30	1.2	1.8
Sandy loam	Lowland	0.50	1.2	1.8
Clay loam	Upland	0.55	1.8	2.4
Clay loam	Lowland	0.70	1.8	2.4
Clay	Upland	0.65	2.4	3.0
Clay	Lowland	0.75	2.4	3.0

Soil Conditions

Across its range, poplar 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 the 3PG model, we developed a matrix of soil and associated soil water availability and fertility based on sand, sandy loams, clay loams, and clay textural classes (Table 1). 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 to very poorly drained. Spatial and tabular soils data were obtained from the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) SSURGO database, which provides spatial and attribute data in common GIS-ready formats for approximately 3,000 soil survey areas across the United States.[2] Soil map units were combined by texture values, and the dominant texture class was assigned to each five-digit ZCTA using the US ZCTA boundary map[3] 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.

Soil fertility and water holding capacity affect SRWC plantation growth. To capture the range of SRWC 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, in which 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 and retention capacities. For example, upslope sands generally have 0.5–1.0% organic matter and would be expected to provide minimal 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, and measurement units were inches of water per foot of soil depth (Table 1).

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 were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center.[4] Monthly averaged solar radiation at each weather station location was obtained from the National Aeronautics and Space Administration (NASA) Atmospheric Science Data Center.[5] 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-yr period from 1995 to 2004. The data input for a given month was the average of 10 monthly values for any given weather variable.

Silvicultural Regime

The regime used for this study varied by location and historical and emerging practice. In the southern states, *P. deltoides* is native and has been grown for decades on a limited number of alluvial river bottom sites (e.g., Red River and Mississippi River). The rotation length for pulpwood has been 8–10 yr, and coppicing has seldom been used because of lower productivity in terms of minimum stem size and the desire to deploy new clones at each rotation (Stanturf et al. 2001). Nevertheless, coppicing has been practiced on a limited basis by small landowners, and smaller average stem diameters are acceptable for SRWC (E. Gardiner, USDA Forest Service, pers. comm., June 24, 2015). We modeled two coppice cycles following the initial planted stand. In contrast, in the central and northern states, emerging silvicultural regimes for hybrid poplar biomass applications have high planting densities and 3- to 4-yr cutting cycles, with multiple coppice cycles to yield five to seven total harvests from one planting, similar to systems used for *Salix* plantings in the Northeast (Stanturf and van Oosten 2014, University of Minnesota Extension 2015, Zalesny et al. 2016a, 2016b).

Genotype

In the southern United States, *P. deltoides* clones have been selected and bred for high productivity on specific sites and generally outperformed hybrids because of greater resistance to *Melamspora* rust (Maisenhelder 1970, Stanturf et al. 2001). In a side-by-side comparison of *P. deltoides* and a *P. deltoides* × *P. nigra* hybrid in Missouri (in the middle of our region), Dowell et al. (2009) found that the *P. deltoides* clones produced almost twice as much biomass as the hybrids after 5 yr despite more rapid early growth by the hybrids. In the northern states, hybrid poplar clones have been developed with high productivity. For our study, we assumed that all plantings modeled would use the best available clones for each site, and we acknowledge that there may be substantial genotype by site or environment interaction differences between deployed clones.

Planting Density

For 3PG model runs for the northern and central states, initial planting densities were set at 4,049 cuttings ac^{-1} (maximum the model allows). For the southern states, the planting density used was 700 cuttings ac^{-1}. Past work with SRWCs has shown that a wide range of initial planting densities may be used and still achieve high yields as long as the silviculture regime allows for reasonably quick site capture and the rotation length is matched to the actual stand development based on the fertilization, weed control, and clonal deployment method used. Hansen and Baker (1979) concluded that closer spacing generally yields the greatest MAI the first several years, but that as plantations get older and fully occupy the site, yields at wider spacing gradually catch up with those at narrower spacing, sometimes equaling or even exceeding them. Cannell and Smith (1980) estimated working maximum yields at approximately 4.46–5.35 $t^{-1}ac^{-1}yr^{-1}$ in 4- to 5-yr rotations. A study in Oklahoma reported slightly higher yields for *P. deltoides* planted at 939

Table 2. Management practices and related costs for poplar SRWCs in the northern United States (hybrid poplar) and southern United States (*P. deltoides*).

Year	Activity	Northern cost/ac	Southern cost/ac
0	Herbicide/weed control	$108	$45
0	Site preparation	$30	$70
0	Mechanical tillage	$45	$65
0	Planting[a]	$1,012	$231
1	Herbicide/weed control ($/ac)		$45
1	Nitrogen fertilizer (60 lb/ac)		$59
2	Nitrogen fertilizer (200 lb/ac)	$196	
2	Nitrogen fertilizer (120 lb/ac)		$118
3	Nitrogen fertilizer (180 lb/ac)		$176
4	Harvest[b]	x[c]	
0	Stump removal (after harvest)	$300	
6	Nitrogen fertilizer (180 lb/ac)		$176
8	Harvest[b]	x	x
0	Stump removal (after harvest)		$300

[a] Planting in the North is 4,049 cuttings/ac and in the South is 700 cuttings/ac.
[b] Harvesting occurs at ages 4, 8, 12, 16, 20, and 24 for hybrid poplar in the North and at 8, 16, and 24 for *P. deltoides* in the South.
[c] Indicates harvest year.

stems ac^{-1} (21.45 t ac^{-1} after 4 yr; Dipesh et al. 2015). Strong and Hansen (1993) noted that conventionally spaced plantations in the temperate region may surpass these yields and that close spacing is not an inherent requirement for high yields.

Coppice Rotation

The total rotation length was 24 yr for all sites. For modeling hybrid poplar in the northern states, the initial planting was cut back at the end of Year 1 and then managed for six successive rotations of 4 yr each similar to the way that willow is managed for bioenergy (Volk et al. 2006). An initial 8-yr rotation from planting was used for modeling *P. deltoides* in the southern states, followed by two coppice rotations of similar rotation length. The initial harvest yield of *P. deltoides* was the MAI of biomass weight times 8. The first coppice yield was assumed to increase to 115% of the initial harvest and the second coppice yield to decline to 80% of the first coppice yield (or 92% of the initial harvest).

Fertilization

Fertilization regimes differed for the two poplar crops. For hybrid poplar, N was applied at Year 2 of each coppice rotation at a rate of 200 lb ac^{-1}. For *P. deltoides* in the southern states, N was applied four times in each 8-yr rotation: 60 lb ac^{-1} in the first year, 120 lb ac^{-1} in the second year, and 180 lb ac^{-1} in each Year 3 and 6. Management practices for hybrid poplar and *P. deltoides* are given in Table 2.

Economic Model

Various approaches have been used to assess the cost structure and financial feasibility of SRWCs (El Kasmioui and Ceulemans 2012). Net present value (NPV) is the most commonly used financial valuation method; it discounts all costs and benefits over a rotation to a reference time. NPV is the present value of future revenues minus the present value of future costs. LEV has long been used for determining optimal forest management practices (Chang 1998). LEV is the NPV of bare land assuming a perpetual land management regime and correctly considers the opportunity cost of capital and land. Another method commonly used is the IRR, or the discount rate at which the present value of costs equals the present value of revenues (i.e., NPV = 0). The higher the IRR, the more desirable it is to plant the SRWC species in that ZCTA.

Two economic criteria—LEV and IRR—were used for this analysis. Economic models were developed using Microsoft Excel to evaluate and compare the profitability of planting *Populus* (both *P. deltoides* and hybrid poplar) on potential sites in the eastern United States. These models focused on the cultivation phase of *Populus* without including the costs of harvest and transportation. The models first converted 3PG outputs, MAI of the volume inside-bark yield (m^3 $ha^{-1}yr^{-1}$), to green weight of biomass (short green t $ac^{-1}yr^{-1}$) using specific volume to dry weight conversion factors of 0.35 metric dry t per m^3. The green weight was then converted to dry weight assuming 50% moisture content. Considering that the yield given is inside-bark biomass, the stumpage price was assumed to be $10/t. The LEV was calculated for each site using an annual discount rate of 5%. The IRR was also calculated using the cash flow of costs (Table 2) and revenues of the total rotation.

Visualization

Modeled yield and economic returns were displayed at the ZCTA level. Two types of maps were produced to display results: one set was based on the five-digit ZCTAs and for the second we used a spatial interpolation technique (simple kriging) to avoid the influence of political boundaries and to illustrate general spatial patterns. 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.

Results and Discussion

Projected Yield Results

Our modeled estimates for hybrid poplar in the northern region ranged from 1.6 to 12.8 ODT $ac^{-1}yr^{-1}$ with a mean of 5.9 ODT $ac^{-1}yr^{-1}$, well within the range of published values. Production rates from 3PG modeling for *P. deltoides* in the South and Midwest states were from 0.5 to 11.9 ODT $ac^{-1}yr^{-1}$ with a mean of 3.9 ODT $ac^{-1}yr^{-1}$, as compared with the 1.3–5.8 ODT $ac^{-1}yr^{-1}$ in the literature (Wright 2010). Hybrid poplar yields in the North Central and Midwest states as summarized by Wright (2010) ranged from 3.2 to 9.3 ODT $ac^{-1}yr^{-1}$ and yields in the Northeast states ranged from 3.7 to 8.1 ODT $ac^{-1}yr^{-1}$. Caputo and Volk (2011) found lower current yields for hybrid poplar in the Midwest and central states—1.8–5.1 ODT $ac^{-1}yr^{-1}$. Zalesny and colleagues (2012) summarized yield of generalist clones as nearly 4.5 ODT $ac^{-1}yr^{-1}$ whereas specialist clones matched to sites were twice as productive, approximately 8.9 ODT $ac^{-1}yr^{-1}$.

Strong and Hansen (1993) presented MAI data for a study with 18 clones by spacing combinations from three planting years that provided a good summary and insight into effects of initial planting density on MAI. The maximum MAI of 2.71 t $ac^{-1}yr^{-1}$ in the 1981 study came at age 6 from a 4,049-stem ac^{-1} planting that was not irrigated (vs. 4.19 t $ac^{-1}yr^{-1}$ irrigated). Fertilization was not included in the study. For the same clone (NE-41), a 2,024-stem ac^{-1} planting produced an irrigated MAI of 5.08 t $ac^{-1}yr^{-1}$ at age 7 and a nonirrigated MAI of 3.79 t $ac^{-1}yr^{-1}$ at age 6. However, the difference in MAI treatments means was not statistically significant.

Research on *P. deltoides* in the southern states has lagged compared with other regions because industrial plantation management

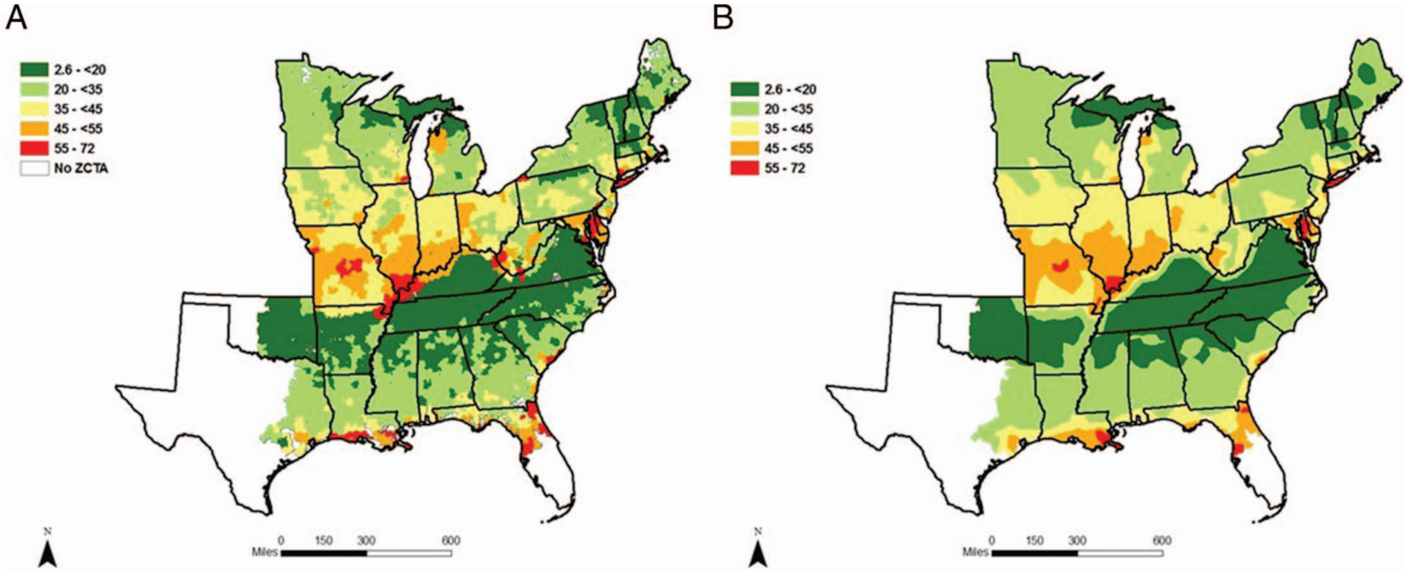

Figure 1. Yield as MAI ($m^3\ ha^{-1}yr^{-1}$, inside bark) of poplars at the five-digit ZCTA level, eastern United States. Yields were modeled using the process model 3PG. Hybrid poplars were modeled north of Arkansas, Kentucky, Virginia, and Maryland; *P. deltoides* was the modeled species in those states and to the South. (A) Modeled MAI at the five-digit ZCTA level. (B) Modeled MAI smoothed using simple kriging. (Conversion $m^3\ ha^{-1}yr^{-1} = 0.446\ ft^3\ ac^{-1}yr^{-1}$).

and most breeding programs have been terminated (Zalesny et al. 2016a). Earlier research produced productive clones that are still used globally in breeding programs. Growth and yield models rely on individual tree volume equations produced by Krinard (1988), and these equations were used by Cao and Durand (1991) to produce a compatible growth and yield model that predicts cubic-foot volume yield for plantations in the Lower Mississippi Alluvial Valley. However, their model is not valid for coppice rotations. Byrd et al. (2015) attempted a model to predict multistem *P. deltoides*, but they concluded the model was not widely useful.

P. deltoides may have the greatest geographic range, but it also has the highest site specificity within that range. It tolerates a wide range of climates but is intolerant of many sites of low fertility or limited water availability (Stanturf et al. 2001). Users of any model should exercise caution when considering regional productivity potential without considering the percentage of available suitable sites in that region that meet the demands of the species. In addition, social and economic constraints on land availability, including ownership, current land use, and special protective status, may render unavailable otherwise biologically suitable sites (e.g., Lazarus et al. 2015, Zalesny et al. 2012).

Our results have a larger yield range, probably because we included experimental yields and incorporated suboptimal sites. Yields were highest in southern Illinois, central Missouri, southern Louisiana, and southern Indiana (Figure 1). The lowest modeled yields were in Kentucky, Tennessee, North Carolina, Oklahoma, Arkansas, and Virginia as well as northern regions of Georgia, Alabama, Mississippi, and South Carolina. For both hybrid poplar in the northern states and *P. deltoides* in the southern states, yields were generally higher in the southern portion of each region and lower in the northern portion. These results (Figure 1) suggest an effect of climate on growth. Zalesny et al. (2012) and Headlee et al. (2013) similarly found higher productivity related to higher temperatures and greater water availability.

The 3PG model incorporates weather, soil texture, and fertility data as well as species-specific parameters to estimate potential volume production. A different methodology for incorporating weather or fertility data than we used could yield different results. For example, we used mean monthly weather data for a 10-yr period to capture the differences in site productivity for the two regions. This approach ignores the possibility of weather extremes, particularly precipitation deficits. In years with a precipitation deficit of 10–25 in., growth may be substantially reduced in comparison to average precipitation years. Alternatively, years with above-average rainfall during the months of June, July, August, and September, when growth is often slowing or shutting down, can produce substantially higher annual growth than the mean. Over a longer rotation it is assumed that the good, average, and poor years of biomass production will average out. However, over the life of a SRWC, a few extreme years could dramatically change the modeled or realized productivity.

Similarly, site fertility has been used to calibrate the model because small changes in this input value can have major impacts on modeled results (e.g., Subedi et al. 2015, Zalesny et al. 2012). Poplars are demanding of nutrients for rapid growth, and fertility differences operationally have significant effects on productivity (Stanturf and van Oosten 2014, Stanturf et al. 2001). We incorporated repeated fertilizer inputs to simulate an operationally intensive crop production. Users should be aware that small fall-downs or failures to maintain the strong fertilization commitment operationally will result in substantial differences in achieved productivity (Dickmann and Stuart 1983, Stanturf et al. 2001), especially on coarse-textured soils (Stanturf and van Oosten 2014).

Modeled results were somewhat higher than recorded in the literature and productivity operationally achieved (Caputo and Volk 2011, Stanton et al. 2002, Stanturf et al. 2001,Wright 2010). The higher modeled yields suggest that more attention to available soil nutrition would be beneficial. Another factor not considered in our modeling was the differences among clones, specifically matching clones to site conditions. We assumed that clones were matched appropriately, but this may be another way to improve operational yields; developing new clones better adapted to suboptimal sites could increase the available land area for SRWCs. Small changes in the

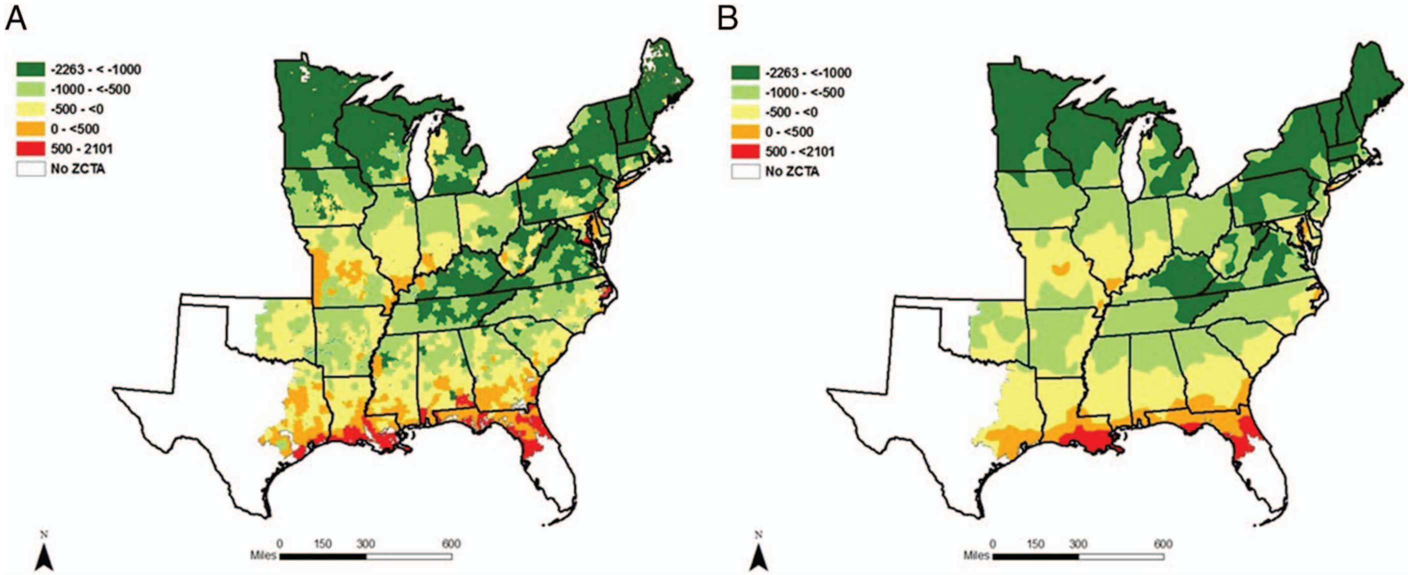

Figure 2. LEV ($ ac^{-1}) of poplars at the five-digit ZCTA level, eastern United States. Hybrid poplars were the modeled species north of Arkansas, Kentucky, Virginia, and Maryland; *P. deltoides* was the modeled species in those states and to the south. Stumpage price was assumed to be $10/t, and a 5% annual discount rate was used. (A) LEV visualized at the five-digit ZCTA level. (B) LEV smoothed using simple kriging.

alpha (canopy quantum efficiency) or the fertility rating may be the best way to account for local conditions and improve modeled results.

Economic Modeling—LEV and IRR

Using the modeled yield predictions at the ZCTA level, we found that the LEVs of *P. deltoides* in the southern states ranged from –$1,411.08 to $1,556.14/ac. The LEV of hybrid poplar crops in the northern states ranged from –$773.55 to $1,563.07/ac. The average IRR for the northern states was 1.1% (median 2.0%, range –13.9 to 11.4%). For the southern states, the mean IRR was –1.6% (median –1.4%, range –14.1 to 14.6%).

It is potentially profitable to plant hybrid poplar as a SRWC biomass crop in the northern United States on 11% of ZCTAs and *P. deltoides* on 29% of the ZCTAs in the southern United States. Some southern coastal sites were excluded because of higher value in other commercial land uses. Excluded areas included Charleston, South Carolina; Freeport, Texas; Dauphin Island, Alabama; Hackberry and Buras, Louisiana; and Brooksville Chin, Apalachicola, Destin, Ft. Walton, Jacksonville, Ponce Inlet, and Sea Hag Marina in Florida.

The lowest LEVs in the Midwest are in Minnesota, Wisconsin, North Michigan, and East Kentucky. Low LEV values are found in the northeastern states of Maine, New York, Massachusetts, Vermont, and New Hampshire. Low LEV values in the

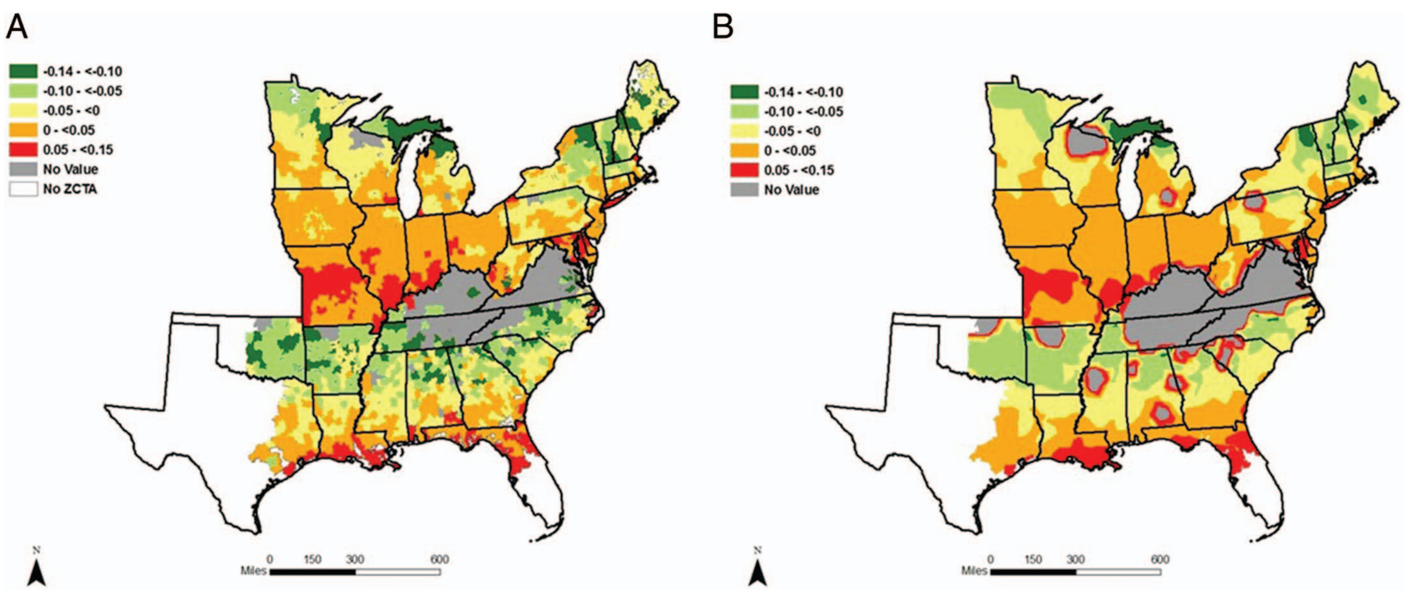

Figure 3. IRR (%) of poplars at the five-digit ZCTA level, eastern United States. Hybrid poplars were the modeled species north of Arkansas, Kentucky, Virginia, and Maryland; *P. deltoides* was the modeled species in those states and to the south. IRR was calculated using the cash flow of costs and revenues of the total rotation. (A) IRR visualized at the five-digit ZCTA level. (B) IRR smoothed using simple kriging.

southern states are in portions of Alabama, Georgia, Louisiana, Mississippi, and Texas as well as North Florida (Figure 2). Northern Michigan and northern New York have the lowest IRR values whereas North Florida and southern portions of Alabama, Georgia, Louisiana, Mississippi, and Texas have the highest IRR values (Figure 3). For both hybrid poplar in the northern states and *P. deltoides* in the southern states, profits were generally higher in the southern portions of their respective ranges and lower in the northern parts of their ranges (Figures 2 and 3). Because the biomass price and discount rate used for LEV and IRR calculations were the same for all sites, the large range of LEVs and IRRs was caused by the variable yields in each site and different costs between northern and southern states.

All things being equal (i.e., clones, weather, and silviculture), poplar yields and economics are sensitive to soil texture (Pinno 2010, Stanturf and van Oosten 2014, Zalesny et al. 2012) because it affects fertility and moisture availability. Although they examined economics of pulpwood rotations of *P. deltoides* rather than biomass, Stanturf and Portwood (1999) illustrate the effect of soil texture on productivity. They examined productivity on three representative soils in the Lower Mississippi Alluvial Valley. The highest productivity sites were on Commerce soils (Aeric Fluvaquents), medium productivity sites were represented by the Tunica-Bowdre soils (Vertic Haplaquepts-Fluvaquentic Hapludolls), and the lowest productivity sites were represented by the Sharkey (Vertic Haplaquepts) soils. Modeled yields were based on Cao and Durand (1991), and management was based on operational industrial practices at the time. Costs were typical for nonindustrial landowners in the Lower Mississippi Alluvial Valley. MAI (green tons per acre) at age 10 under these operational assumptions were 6.9 (Commerce), 5 (Tunica-Bowdre), and 4.2 (Sharkey). Afforestation with *P. deltoides* was profitable under most conditions; profitability was influenced by including a coppice rotation and by stumpage, volume yields, and taxes as well as choice of interest rate and availability of subsidies (Stanturf and Portwood 1999).

Our study benefits the emerging bioenergy economy by estimating yields and potential profitability at a fine spatial resolution for *P. deltoides* (Eastern cottonwood) and hybrid poplars using the five-digit ZCTA. Southern Illinois, central Missouri, southern Louisiana, and southern Indiana have the highest yield production. Kentucky, Tennessee, North Carolina, Oklahoma, Arkansas, and Virginia as well as southern regions of Georgia, Alabama, Mississippi, and South Carolina have the lowest potential yield production. Higher yields in the central portion of the operable range of poplar also resulted in correspondingly higher estimates of LEV and IRR. *P. deltoides* had attractive IRR in some regions, with a maximum of 14.6% in the southern states, and hybrid poplars had a maximum of 11.4% in the northern states. The yield numbers can be used for further research on sustainability of carbon sequestration (Dowell et al. 2009). Continued research could improve the parameterization of the 3PG model with attention placed on the leaf phenology and biomass partitioning routines to better incorporate clonal differences. Renewed emphasis on breeding and matching clones to site would improve productivity (Zalesny et al. 2016a). Profitability would be improved by lowering costs; for example, mechanical cultivation for weed control would no longer be necessary if new herbicides were developed that could be applied during the growing season or transgenic clones with herbicide tolerance were approved (Stanturf and Portwood 1999). Just as matching clones to site is important, appropriate silvicultural regimes tailored for clones and sites are needed, in particular optimal spacing and fertilization regimes (Zalesny et al. 2016a). Encouragingly, new efforts are underway to improve our understanding of *P. deltoides* biomass production (Coleman et al. 2004, Coyle et al. 2006, 2013, Souter et al. 2015).

The modeling framework presented here can be extended to incorporate risk from weather extremes and estimate the climate change mitigation potential of SRWC using poplars. The results can be used in bioenergy siting decision support systems (e.g., Perdue et al. 2011) as a filter to identify potential areas for more detailed investigation. This approach will be most useful for choosing species to plant on former farmland or when landowners may be willing to change species on cutover forestland.

Endnotes

1. For details, see https://www.census.gov/geo/maps-data/data/tiger-line.html.
2. For details, see http://sdmdataaccess.nrcs.usda.gov/.
3. For details, see www.census.gov/geo/reference/zctas.html.
4. For details, see https://www.ncdc.noaa.gov/cdo-web/.
5. For details, see https://eosweb.larc.nasa.gov/sse/.

Supplemental Podcast

This article includes a podcast interview. Visit the online version of this article to listen to the podcast.

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