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Research paper

SRWC bioenergy productivity and economic feasibility on marginal lands

Solomon B. Ghezehei*, Shawn D. Shifflett, Dennis W. Hazel, Elizabeth Guthrie Nichols

Department of Forest and Environmental Resources, NC State University, Raleigh, NC 27695, USA

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ABSTRACT

Evolving bioenergy markets necessitate consideration of marginal lands for woody biomass production worldwide particularly the southeastern U.S., a prominent wood pellet exporter to Europe. Growing short rotation woody crops (SRWCs) on marginal lands minimizes concerns about using croplands for bioenergy production and reinforces sustainability of wood supply to existing and growing global biomass markets. We estimated mean annual aboveground green biomass increments (MAIs) and assessed economic feasibility of various operationally established (0.5 ha–109 ha) SRWC stands on lands used to mitigate environmental liabilities of municipal wastewater, livestock wastewater and sludge, and subsurface contamination by petroleum and pesticides. MAIs (Mg ha^{-1} yr^{-1}) had no consistent relationship with stand density or age. Non-irrigated *Populus*, *Plantanus occidentalis* L. and *Pinus taeda* L. stands produced 2.4–12.4 Mg ha^{-1} yr^{-1}. Older, irrigated *Taxodium distchum* L., *Fraxinus pennsylvanica* L., and coppiced *P. occidentalis* stands had higher MAIs (10.6–21.3 Mg ha^{-1} yr^{-1}) than irrigated *Liquidambar styraciflua* L. and non-coppiced, irrigated *P. occidentalis* (8–18 Mg ha^{-1} yr^{-1}). Natural hardwood MAIs at 20–60 years were less than hardwood and *P. taeda* productivities at 5–20 years. Unlike weed control, irrigation and coppicing improved managed hardwood productivity. Rotation length affected economic outcomes although the returns were poor due to high establishment and maintenance costs, low productivities and low current stumpage values, which are expected to quickly change with development of robust global markets.

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1. Introduction

In the U. S., the 2007 Energy Independence and Security Act sets a target of 136 billion liters (36 billion gallons) of renewable fuels for road transportation by 2022 (U.S. Congress, 2007; Al-Riffai et al., 2010). The National Defense Authorization Act of 2010 mandates that each Federal agency produces or consumes 25% of total energy from renewable energy sources beginning in 2025. In Europe, renewable energy directive 2009/28/EC dictates that by 2020, 20% of total energy and 10% of transport fuel consumptions of EU members should be from renewable energy sources (Scarlat et al., 2013). These mandates have re-invigorated national interest in renewable energy feedstocks and already shifted cropland use for bioenergy feedstocks, thus inflating commodity prices for food crops and livestock (Swinton et al., 2011). The U.S. needs 16 to 21 million ha of non-contentious land in order to meet the above target for cellulosic ethanol by 2022, (Lewis and Kelly, 2014) and Europe requires 17 to 30 million ha of land to achieve the 10% bioenergy target by 2020 (Scarlat et al., 2013).

To avoid using croplands for energy production and damaging forests and wetlands due to fast growing wood pellet production (Guo et al., 2015), worldwide efforts are underway to evaluate the use of marginal lands for bioenergy production (Gopalakrishnan et al., 2011; Fritz et al., 2012; Zumkehr and Campbell, 2013; Kang et al., 2013; Kells and Swinton, 2014; Lewis and Kelly, 2014; Stoof et al., 2014). The definition of marginal land varies (Kang et al., 2013) and has been used subjectively (Richards et al., 2014) but broadly describes lands not under cultivation due to low agro-economic values for major agricultural crops (Gopalakrishnan et al., 2011). The use of marginal lands for bioenergy production is appealing partly due to significant availability of marginal lands (Liu et al., 2011). Globally, the size of marginal lands available for bioenergy production could be 100 million to 1 billion ha (Milbrant and Overend, 2009; Zhuang et al., 2011; Kang et al., 2013). For most

* Corresponding author. NC State University, Campus Box 8008, Raleigh, NC 27695-8008 USA.
E-mail address: sbghezeh@ncsu.edu (S.B. Ghezehei).

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of the southeastern U.S., marginal croplands are largely wooded areas with poor soil productivity (Swinton et al., 2011). Lands may be “marginal” for conventional cropland use, but they may be appropriate and productive for bioenergy crops (Dickmann, 2006). Marginal land use for woody biomass production is also of intense interest given growing sustainability concerns of feedstock supplies to existing wood product markets and growing bioenergy markets. As urbanization continues to reduce forested acreage in the southeastern U.S., robust timber and wood pellet markets may alleviate this decline by expanding woody biomass production to marginal lands (Wear and Greis, 2013).

For the southeastern U.S., state, national, and international legislative mandates have grown bioenergy markets, particularly wood pellet production. In 2012, for instance, the U. S. produced over 21% of global wood pellet, which is expected to reach 45.2 million tonne by 2020 (Guo et al., 2015). Annual European wood pellet import is expected to reach over 21.8 million by 2015 (O'Carroll, 2012) predominantly expected from the southeastern U.S. where 21 wood pellet plants were in operation by 2013 (RISI, 2013). U.S. wood pellet exports to Europe increased from 1.3 million tonne in 2012 (Guo et al., 2015) to 2.9 million tonne in 2013, mainly from the southeastern U.S. due to high wood supply and proximity to processing plants and maritime shipping ports to European markets, thus reducing transportation costs, which make up to 25% of wood pellet price at delivery (Dickmann, 2006; EIA, 2014). Growing demand is evident in the recent establishment of two wood pellet plants (Mullins et al., 2014) and several maritime port expansions in eastern North Carolina (NC) to meet regional and local wood pellet demands.

Sustainability guidelines now under development in Europe are expected to restrict the use of forestlands for bioenergy production. The International Wood Pellet Buyers Group, for instance, opposes bioenergy use of wood from natural wetlands, major forest component in the southeastern U.S. (IWPBG, 2011). In the U. S., the definition of eligible woody biomass for biofuels production credit under RFS2 (U.S. Congress, 2007) is expected to restrict wood feedstocks from natural forest stands that comprise about 80% of southeastern forests (Huggett et al., 2013). Several studies evaluated biomass productivity of managed sycamore, sweetgum, green ash, and cottonwood plantations (Torreano and Frederick, 1988; Kennedy, 1981; Francis, 1982; Krinard and Kenney, 1983) and natural hardwood stands (Messina et al., 1986; Gower et al., 1985) for energy production in the coastal southeastern U.S. Currently, the species composition of managed woody bioenergy plantations likely includes *Populus* species, *Plantanus occidentalis* L. (sycamore), *Liquidambar styraciflua* L. (sweetgum), and *Pinus taeda* L. (loblolly pine) (Kennedy, 1981; Perlack et al., 1986; Dickmann, 2006).

The economic feasibility of woody biomass productivity varies considerably based on site conditions, planting densities, management, rotation length and species. The prices of the woody bioenergy products is more critical to economic feasibility than productivity (Schweier and Becker, 2013). Currently, profitability of *Populus* and *Salix* cannot compete with profits from traditional grass crops (hay) on marginal lands since woody bioenergy markets are not established (Kells and Swinton, 2014). For the southeastern U.S., markets already exist for traditional wood product uses, and the wood pellet market is established and growing (RISI, 2013). The efforts of the EU to provide stable and robust market environment for bioenergy is expected to play a leading role in increasing the values of bioenergy products, particularly in the southeastern U.S.

Information on marginal land suitability for sustainable bioenergy production is lacking (Liu et al., 2011) and little is known about the economic feasibility of what trees species to grow, which marginal lands to use, and total capacity for production. We define marginal lands as idle and abandoned croplands and pasturelands, woods, lands with environmental liabilities, contaminated and permitted-use lands such as wastewater application fields. We evaluated wood biomass productivity of managed stands on diverse marginal lands with stand ages of five to 20 years and sizes ranging from 0.1 to 149 ha for the aforementioned species, *Taxodium disctchum* L. (bald cypress) and *Fraxinus pennsylvanica* (L.) Marshall (green ash). Their productivities were compare with those of native hardwood forest stands and their economic viability were assessed to determine what type of woody biomass to grow on marginal lands for bioenergy production within five to 20 year rotations. Although the stands were not managed as systematically and carefully as research plots would have been managed, they provide real-world operational productivity estimates of species recommended as SRWCs on various marginal lands. The stands are used to mitigate problems such as nutrient management or groundwater contamination by fuels or pesticides.

2. Materials and methods

2.1. Site description

We inventoried seven sites in NC (Fig. 1); details of size, age and type of the sites, mean annual rainfall, irrigation (if provided), stand species and management, and soil profiles are provided in Table 1. Annual rainfall was determined as the average rainfall of each year during the lifetime of each stand using weather data provided by the State Climate Office of NC. Mean annual irrigation was calculated from facility records for the last ten years for Garner and the last three years for Edenton.

Because Elizabeth City site was planted in 2006 and 2007, productivity was determined for each stand establishment. The stands at Edenton were coppiced in 1997 and 2008 by a professional logger so productivity represents growth from second coppice (during third rotation). At the other sites, stand management was minimal with no thinning. Weed control consisted of periodic mowing at all sites except Mount Olive where glyphosate (*N*-(phosphonomethyl)-glycine) was also used as a chemical control. At the Johnston county (JC) site, mean soil nitrate and Kdjedahl nitrogen concentrations in 2011 (nine years after land application) were 2.6 ± 1.9 $N{-}NO_3^-$ mg kg^{-1} soil and 869 ± 355 TKN mg kg^{-1} soil, respectively and *P. taeda* was planted in 2007. The distribution of nitrogen in the material used for the lagoon closure at Nash county is not known. For the municipal wastewater land application sites, mean nitrogen and phosphorus loadings per tree were 0.14 kg and 0.020 kg respectively. Since nitrogen and phosphorous loadings were addressed only for some of the sites (due to the size of the sites, significant investment would be required to adequately address this point) and coefficients of variation of the means were nearly 50% if not higher, they are not discussed further.

2.2. Inventory of aboveground biomass

To determine stand productivity, tree heights and outside-bark diameters at breast height (DBHs) were measured for individual trees either by establishing random 0.04 ha sampling plots or inventorying all trees in a stand (Table 1). Tree heights and DBHs were determined using tree height poles, Suunto clinometers, logger tapes, and Lufkin Executive DBH measuring tapes. At least 10% of trees in the sampling plots were measured twice to provide field quality control for precision (Supplementary Table 2).

Productivity was determined as mean annual green aboveground biomass increment (MAI) in metric tons per hectare per year (Mg ha^{-1} yr^{-1}) by multiplying wood volumes (m^3) and wood density at 50% moisture content (kg m^{-3}). The assertion of 50% moisture content of standing *Populus* trees is supported by our

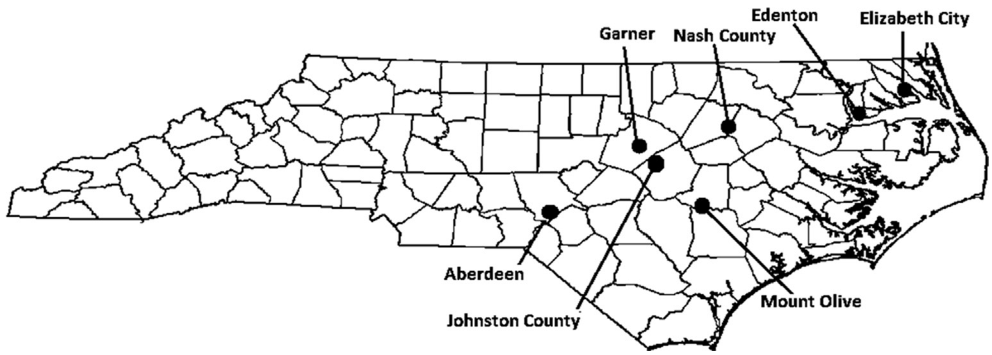

Fig. 1. A map of locations of the inventoried stands in NC.

findings from standing hybrid poplars at Aberdeen, Elizabeth City and Nash county. The wood density of each species (Supplementary Table 1) was determined by multiplying medium density or average density obtained from a wood density database (World Agroforestry Centre, 2012) by 1.7. Outside-bark woody volumes were estimated using measured heights and DBHs and literature-derived equations (Supplementary Table 2). Because most of the stands were 10 years old or younger, we tested accuracies of literature-derived volume equations of *L. styraciflua and P. occidentalis* with equations developed by destructive sampling at Edenton and Mt. Olive. For both species, coefficients of determination of the literature-derived equations ($R^2 = 1$) were higher than those of the measurement-derived equations ($R^2 = 0.96$). Although form-class segmented volume equations (Clark et al., 1991) were also considered, they were not used in this study as the inventoried trees were too small to meet size requirements of the equations.

2.3. Economic analyses

The economic feasibility of growing the stands for biomass feedstock was assessed by calculating net present value or NPV (El Kasmioui and Ceulemans, 2013), internal rate of return or IRR (Schmithüsen et al., 2014) and land expectation value (LEV) using costs and revenues, discount rates of 3%, 5% and 7% and various rotation lengths (actual ages and three extended rotations). The U.S. Forest Service Quick-Silver software (Vasievich, 1999) Version 7.0 was used to calculate IRR and NPV. Where stand NPV was positive, equivalent annual value (EAV) was also calculated (Friday et al., 2000) to determine stand values in terms of annual income.

Costs of establishing and managing the stands were estimated based on available management history (Table 1) by discounting current activity and material costs for forestry or agricultural activities (University of Illinois Extension (2012)) to the years of

Table 1
Site information for inventoried stands in NC.

Site (age), site size (ha), sampled from	Mean rainfall, irrigation[a] (mm per annum)	Site details	Tree species	Trees per hectare	Weed/stand management	Soil series
Aberdeen (15 yrs) 1.4 ha (3 plots)	1200 None	Groundwater remediation (pesticides)	*Populus*	1079	Mowing/none	Vaucluse loamy sand
Edenton (5&6 yrs) 145 ha (6 plots)[c]	1250 1100[a]	Municipal wastewater land application treatment of primary wastewater	*L. styraciflua* *P. occidentalis*	5424 1798	Mowing, coppice every 6 years	Fine sandy loam (Altavista, Dogue, Tomotley); Silt loam (Chowan, Roanoke); Loamy sand (Conetoe, State); Dorovan muck, Portsmouth loam, Roanoke silt loam
Elizabeth City (6 & 7 yrs) 2.0 ha (entire stand)	1250 None	Groundwater remediation (petroleum/fuels)	*Populus*	2041	Mowing/trees trimmed to 4 feet every 2 yrs	Udorthent, loamy
Garner (20 yrs) 109 ha (11 plots)[b]	1150 1368[a]	Municipal wastewater land application treatment of primary wastewater	*F. pennsylvanica* *L. styraciflua* *P. occidentalis* *T. distchum*	1359 1866 1273 1137	Mowing/none	Sandy loam (Altavista Appling, Buncombe Cecil, Chewacla, Lynchburg, Mantachie, NorFolk, Pacolet, Vance, Warne, Wedowee, Worsham); Silt loam (Congaree, Wehadkee) Loamy sand (Durham, Louisburg); Soils (Wehadkee, Bibb).
Johnston county (6 yrs) 3.7 ha (10 plots)	1150 None	Nutrient remediation of former swine waste land application field	*P. taeda*	1076	None/none	Cecil loam, sandy loam (Gillead, Marlboro), Pacolet loam.
Mount Olive (5 yrs) 50 ha (7 plots)	1200 None	Municipal wastewater land application treatment of tertiary wastewater	*P. occidentalis*	1292	Mowing, Glyphosate/trees trimmed to 5 feet every year with herbicide	Sandy loam (Bibb, Craven, Autryville, Norfolk, Johns, Rains); Loamy sand (Ruston, Wagram, Kalmia, Goldsboro, Norfolk); Loam (Chewacla, Johnston, Pantego), soils (Johnston, Pamlico, Marvyn, Gritney); Weston loamy fine sand
Nash county (10 yrs) 0.13 ha (entire stand)	1200 None	Alternative lagoon closure procedure	*Populus*	1373	None/none	Bonneau loamy sand, Gritney sandy loam

[a] Mean irrigation was determined based on recorded storage during the last three years for Edenton and last 10 yrs for Garner.
[b] Number of plots per species was F. pennsylvanica (3), L. styraciflua (2), P. occidentalis (2), and T. distchum (4).
[c] Number of plots per species was L. styraciflua (2) and P. occidentalis (4).

occurrence. No land rent or property taxes were considered. Costs during site establishment and management included groundcover suppression (using herbicides, mowing and sub-soiling), installation and maintenance of irrigation systems for irrigated stands (Wichelns et al., 1996), planting labor (NC Forest Services, 2014a) and post-planting weed management costs. Costs per seedling of \$0.06 for loblolly pine and \$0.30 for the other species were used (ArborGen, 2013–2014; NC Forest Services, 2014b). Site maintenance costs included mowing and irrigation maintenance expenses (Wichelns et al., 1996; University of Illinois (2012)). To determine harvest and delivery costs, we used average hauling distance haul rates published by Timber Mart-South (TMS) for NC (region 2, first quarter of 2014) for a 40-tonne net log truck at an assumed rate of 2.13 km per liter (5 miles per gallon) at \$1 per liter (\$ 3.80 per gallon) diesel. No storage costs were considered as same-day harvesting and trucking was assumed.

We used two approaches to obtain a stumpage price for trees sold as energy feedstock. In the first, we used TMS delivered prices FOB Mill of pulpwood hardwood and subtracted harvest and delivery costs estimated in the manner described above and assuming all residual costs were paid as stumpage to landowners. The resulting estimated stumpage was \$4.33 per green tonne. In the second approach, we used average hardwood pulpwood stumpage price in the same report, which is \$4.42 per green tonne. For most of the southeastern U.S. including the region where our stands are located, no biofuel industry exists yet, however, two new wood pellet plants have recently been constructed that are rumored to pay "about pulpwood prices", although actual prices are not publically available. Given the small difference between the calculated and the reported average NC stumpages, we used reported stumpage in our analyses. For the younger stands, rotation was extended to 15, 18 and 20 years by projecting productivity of the stands using species-specific MAIs obtained from Dickens et al. (2011) and references therein. Running scenarios for younger stands allowed evaluation of the effect of rotation lengths.

To analyze effects of increased stumpage values on economics feasibility, the stands were further analyzed using a TMS southwide average stumpage value of \$11.16 per green tonne (fourth quarter of 2014) at rotation lengths of actual age, 10, 12, 15, 18 and 20 years. Where the south-wide stumpage price did not produce positive returns, break-even analyses were performed at these rotations. We did not address economies of scale of the stands as there is a great need to have larger studies established to address costs and economic profitability, which depend not only on biomass yields but also a variety of factors from site maintenance to product delivery to markets.

3. Results and discussion

3.1. Biomass productivity

MAIs of the inventoried stands are presented in Fig. 2. Non-irrigated *Populus* and *P. occidentalis* stands had MAI of 2.4–5.3 Mg ha^{-1} yr^{-1} and 2.5–7.6 Mg ha^{-1} yr^{-1} respectively. Because water deficit can negatively affect *Populus* productivity (Monclus et al., 2006), lack of irrigation and periodic drought from 2005 to 2010 (NC Division of Water Resources, 2009) may have limited MAIs of the *Populus* stands we studied. Non-irrigated *P. taeda* had MAI range of 5.1–12.4 Mg ha^{-1} yr^{-1} during the same drought period without any weed suppression whereas the *Populus* and *P. occidentalis* stands were mowed periodically until canopy closure. More productive stands were older and irrigated *T. distchum* and *F. pennsylvanica* stands and irrigated and coppiced *P. occidentalis* stands (Fig. 2). The 19-year-old *F. pennsylvanica* stand was the most productive with MAI of 10.6–21.3 Mg ha^{-1} yr^{-1}. The 20-year-old *T. distchum* had MAI of 19 ± 0.87 Mg ha^{-1} yr^{-1} while productivity of 20-year-old *F. pennsylvanica* stands ranged between 10.8 and 13.5 Mg ha^{-1} yr^{-1}. Moderate to high MAIs were observed for coppiced *L. styraciflua* (10–12.1 Mg ha^{-1} yr^{-1}) and *P. occidentalis* (8–18 Mg ha^{-1} yr^{-1}).

Our results suggest that irrigation and coppicing can improve biomass productivity on marginal lands and that opportunities to merge existing land applications of wastewater from municipalities, livestock feeding operations, aquaculture, food processing industries etc. With biomass production should be further explored. Sites with weed control were not necessarily more productive than sites without weed control although tree species varied among sites. As shown in Fig. 2, longer rotations generally increased MAI of *Populus*, while *F. pennsylvanica*, *L. styraciflua* and *P. occidentalis* had similar or generally higher MAIs at shorter rotations. Some marginal lands could be better producers than others as evidenced by higher productivity of non-irrigated *Populus* at Nash county (10 years old) than Aberdeen (15 years old) and higher productivities of irrigated *P. occidentalis* and *L. styraciflua* at Edenton (5 and 6 years old) than Garner (20 years old).

Studies of *Populus* productivity on marginal lands in the U.S. provide a wide MAI range. Zalesny et al. (2007) reported aboveground MAI of 0.31–1.5 Mg ha^{-1} yr^{-1} for 1.7 year-old high density stands (3472 trees ha^{-1}) in Wisconsin irrigated with landfill leachate. Felix et al. (2008) reported MAI of 5.5 Mg ha^{-1} yr^{-1} for *Populus* trees grown in trenched municipal waste bio-solids in southern Maryland on three to six year rotations with no site maintenance. For *Populus* stands irrigated with municipal wastewater effluent, dry mass MAIs of 20 Mg ha^{-1} yr^{-1} in central Florida (Stricker et al., 2001) and 21–50 Mg ha^{-1} yr^{-1} for a two-year growth of a high density stand in north Florida (Minogue et al., 2012) have been reported. There are additional studies but conversion of the reported productivities to MAIs can lead to overestimations due to small study sizes (Kaczmarek et al., 2013) or young stand ages (Shifflett et al., 2014).

Published information on productivity of the other species we inventoried on marginal lands is limited. MAI of *P. taeda* in this study (8.5 Mg ha^{-1} yr^{-1}) was much greater than MAIs from other studies of 3.6 Mg ha^{-1} yr^{-1} (Samuelson et al., 2004) and 3.9 Mg ha^{-1} yr^{-1} (Allen et al., 2005) for six-year-old pines. Frederick et al. (1998) reported that *L. styraciflua* at a municipal land application site in NC produced 3.8 Mg ha^{-1} and 9.4 Mg ha^{-1} annually at five and ten years of age respectively. Coppiced five-year-old *P. occidentalis* had MAIs of 7–17 Mg ha^{-1} yr^{-1} whereas non-coppiced *P. occidentalis* had MAIs of 9.6 Mg ha^{-1} yr^{-1} and 9.4 Mg ha^{-1} yr^{-1} at five and ten years respectively at different wastewater land application sites in NC. MAIs of our non-coppiced stands are comparable to MAIs of managed stands in the northeast U.S. of 7 Mg ha^{-1} yr^{-1} (Tharakan et al., 2001), and north central U.S. of 9 Mg ha^{-1} yr^{-1} (Netzer et al., 2014).

Natural hardwood stand management normally requires minimal to no site preparation and maintenance as forest stands are allowed to regenerate and thin naturally, requiring longer rotations (20–60 years) to reach acceptable size. For pulpwood and bioenergy products, rotations do not need to be as long. Data evaluating natural hardwood productivity for shorter rotation periods (5–20 years) in NC are not well documented. Merz (1965) reported *P. occidentalis* productivity of 6.2 Mg ha^{-1} yr^{-1} for a 17-year-old natural stands in NC. *F. pennsylvanica* has had little MAI data published and the impending threat of *Agrilus planipennis* (emerald ash borer) is likely to reduce stand productivity and its consideration for commercial use. In Georgia, 27-year-old pulpwood stands with 80% composition of *F. pennsylvanica* had MAI of 6.0 Mg ha^{-1} yr^{-1} (Kennedy, 1990). The MAIs of these two species were lower than MAIs of our irrigated stands (Fig. 2), and similar to that of our non-irrigated *P. occidentalis*.

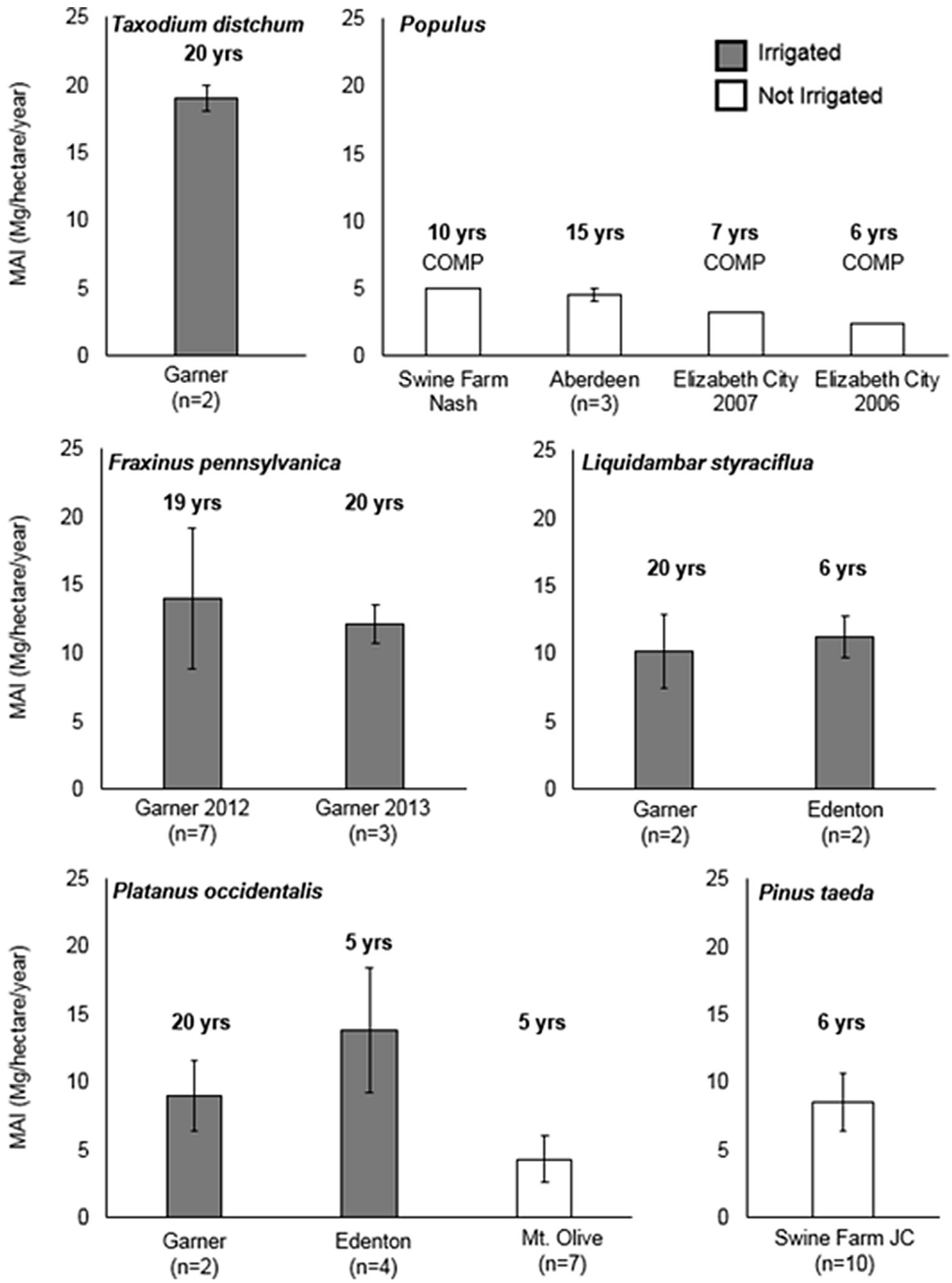

Fig. 2. Green MAI (±1 standard deviation) for the inventoried stands (with ages shown above the bars). "COMP" denotes comprehensive inventories (from Nash county and Elizabeth City) involving all living trees.

Gardner et al. (1982), Messina et al. (1986), and Gower et al. (1985) provide extensive evaluations of productivity of natural hardwood stands in eight ecosystem types in southeastern U.S. ("Muck swamp", "Wet flat", "Red river bottom", "Black river bottom", "Branch bottom", "Bottomland", "Coves, gulfs, lower slopes", and "Upland slopes and Ridges"). Fig. 3 and Fig. 4 compare MAIs of the natural stands with our observed MAIs based on stand density and age. There are no clear relationships between stand density and MAIs for the natural stands nor the stands we inventoried where stand densities varied for a particular species (Fig. 3). As a result, SRWCs can be planted at high density to maximize biomass production per unit land and facilitate biomass availability in shorter rotations in order to meet the rising feedstock demands. Likewise, stand age did not particularly increase or decrease MAIs of the natural stands (Fig. 4).

MAIs of *F. pennsylvanica* and *T. distchum* in our study exceeded MAIs of the natural stands, which ranged from 5.9 to 16 Mg ha^{-1} yr^{-1}, particularly in bottom and swamp areas at 20 years (Fig. 4). More importantly, MAIs of the much younger *P. taeda* (non-irrigated and a softwood) and *P. occidentalis* (irrigated, coppiced and non-coppiced) on marginal lands were similar to or higher than MAIs of the 20-year-old natural stands (Fig. 4). Even without irrigation, *P. taeda* stands we inventoried had MAIs (5.14–12.4 Mg ha^{-1} yr^{-1}) comparable to most of the natural stands

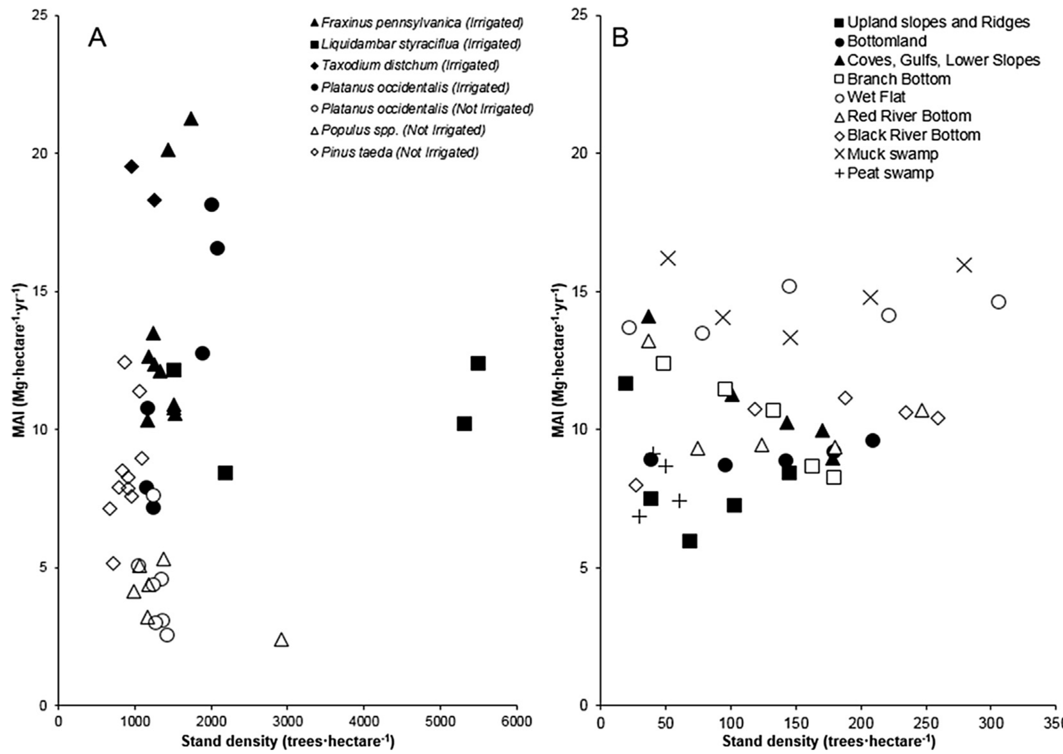

Fig. 3. Green MAI versus stand density for trees on (A) marginal lands in NC and (B) natural stands inventoried by Gardner et al. (1982), Messina et al. (1986), Gower et al. (1985).

(except "Muck swamp" and "Wet flat" stands). These data justify further evaluations of marginal land productivity to meet growing bioenergy needs versus utilization of natural hardwood stands for non-traditional forestry product resources.

3.2. Economic analyses

The resultant low (negative) values of the economic parameters (Table 2) show that most stands were economically unfeasible as

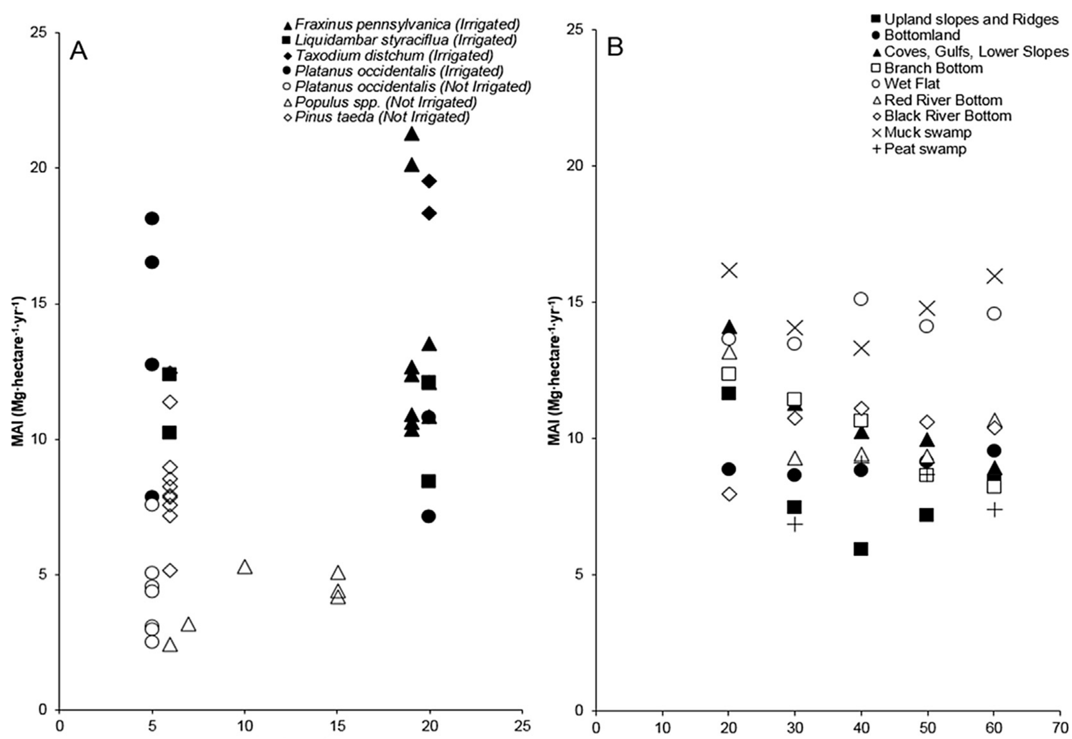

Fig. 4. Green MAI versus age for trees on (A) marginal lands in NC and (B) natural stands inventoried by Gardner et al. (1982), Messina et al. (1986), Gower et al. (1985).

Table 2
Results of economic analyses of the *Populus* (*Pop*), *P. occidentalis* (*Po*), *L. styraciflua* (*Ls*), *P. taeda* (*Pt*), *T. disctchum* (*Td*) and *F. pennsylvanica* (*Fp*) stands.

Economic metric	Age (yrs.)	Discount rate	Aberdeen	Edenton		Elizabeth City	Garner					Johnston county	Mount Olive	Nash county
			Pop	*Po*	*Ls*	*Pop*	*Fp* (19 yrs)	*Fp* (20 yrs)	*Ls*	*Po*	*Td*	*Pt*	*Po*	*Pop*
LEV ($ ha^{-1})	Actual	3%	−249	−682	−1818	−709	−667	−911	−733	−836	−407	−53	−620	−335
	15		−249	−268	−1038	−318	–	–	–	–	–	624	−129	−105
	18		−202	−80	−822	−205	–	–	–	–	–	770	−32	0
	20		−128	41	−676	−134	–	−911	−733	−836	−407	851	28	64
	Actual	5%	−311	−704	−1790	−716	−858	−904	−1050	−957	−689	−82	−620	−364
	15		−311	−645	−1244	−430	–	–	–	–	–	362	−257	−208
	18		−290	−548	−1115	−362	–	–	–	–	–	426	−203	−147
	20		−244	−485	−1026	−319	–	−904	−1050	−957	−689	456	−170	−112
NPV (EAV) (in $ ha^{-1})	Actual	3%	−406	−573	−997	−856	−1228	−1276	−1495	−1364	−937	−69	−653	−430
	15		−406	−308	−810	−529	–	–	–	–	–	548 (46)	−71	−250
	18		−382	−260	−772	−452	–	–	–	–	–	682 (50)	99	−168
	20		−328	−236	−751	−410	–	−1276	−1495	−1364	−937	755 (51)	180	−122
	Actual	5%	−454	−586	−997	−831	−1375	−1404	−1587	−1442	−1177	−95	−639	−449
	15		−454	−444	−900	−625	–	–	–	–	–	289 (28)	−269	−340
	18		−455	−431	−890	−591	–	–	–	–	–	343 (29)	−185	−301
	20		−429	−430	−888	−577	–	−1404	−1587	−1442	−1177	365 (29)	−159	−284
Stumpage values ($ t^{-1})	Actual	–	119	305	300	22	467	366	434	321	676	91	38	94
	15		119	915	749	280	–	–	–	–	–	597	502	249
	18		215	1098	899	371	–	–	–	–	–	765	685	342
	20		277	1220	999	431	–	366	434	321	676	877	807	404
IRR (%)	Actual	–	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA	[a]NA
	15		[a]NA	[a]NA	[a]NA	[a]NA	–	–	–	–	–	9.18	[a]NA	[a]NA
	18		[a]NA	1.17	[a]NA	[a]NA	–	–	–	–	–	9.12	1.13	1.42
	20		[a]NA	1.50	[a]NA	[a]NA	–	[a]NA	[a]NA	[a]NA	[a]NA	8.97	1.61	2
Total present-value costs ($ t^{-1})	Actual	3%	−1542	−4999	−4643	−1236	−4826	−4552	−4255	−3786	−6034	−1112	−1100	−1386
	15		−1542	−8762	−6978	−3118	–	–	–	–	–	−4670	−4458	−2427
	18		−2100	−9432	−7164	−3566	–	–	–	–	–	−5441	−5379	−2903
	20		−2414	−9785	−7206	−3810	–	−4552	−4255	−3786	−6034	−5861	−5903	−3168
	Actual	5%	−1238	−5884	−5451	−1161	−3778	−3590	−3430	−3057	−4581	−1006	−1095	−1223
	15		−1238	−8552	−7040	−2528	–	–	–	–	–	−3546	−3494	−1942
	18		−1648	−9101	−7191	−2750	–	–	–	–	–	−3904	−3986	−2199
	20		−1821	−9392	−7225	−2847	–	−3590	−3430	−3057	−4581	−4053	−4221	−2318

[a] NA shows IRR values less than or equal to zero.

established and managed at current local (NC) stumpage prices for energy feedstocks. Factors that contributed to infeasibility included relatively high costs of establishment including weed management, subsoiling, seedlings, irrigation at the irrigated sites and extremely low stumpage price. In addition, the stands were not necessarily established and managed for high growth rates. While lower productivity, high costs or both made the other stands economically unfeasible, JC had positive returns due to high *P. taeda* productivity, absence of irrigation costs and lower establishment costs. We included the costs of installing irrigation because productivity would reflect the benefit of irrigation. However, it could be argued that because irrigation of some approved crops was required under their state discharge permit, the cost of irrigation could have been excluded, and only costs and incomes over and above normal irrigation practices could be included. Rotation length affected NPVs, LEVs and stumpage values indicating that determining rotation length using economic criteria is feasible.

Although the economic parameters in Table 2 are not encouraging for bioenergy SRWCs production, few expect a viable industry to develop with the low NC stumpage values for pulpwood, which are historically among the lowest in the Southeast and can be expected to increase considerably as energy markets develop. As shown in Table 3, *Populus* stands at Aberdeen, Elizabeth City and Nash county had positive returns and Nash county showed profitability even at higher discount rate (5%) using south-wide stumpage value ($11.16 per green tonne). *P. occidentalis* stands at Edenton and Mount Olive showed positive returns in 10–12 years. Where the south-wide stumpage prices did not produce positive returns, stumpage prices required to break-even ranged between $ 11.33 and $ 61.56 per green tons.

The economic performance of such stands can be improved by subsidization at establishment phase (Mitchell et al., 1999; Kasmioui and Ceulemans, 2013). Poor soils cannot support sufficient woody biomass productivity to justify intensive forestry investment on SRWCs (Dickmann, 2006) and the wastewaters at our study sites are not nutrient-rich. Active fertilization would benefit productivity of the stands by increasing their growth rates and supporting higher density, thus improving productivity and economic feasibility of the marginal lands for bioenergy production. SRWCs can grow well on marginal lands where water supply is not limiting; thus, irrigation systems with low capital and running costs should be preferred (Schweier and Becker, 2013). Cost-effective ways of integrating irrigation and fertilizer applications should be implemented in order to maximize productivity and economic feasibility.

Some studies have evaluated scenarios for the U.S. biofuels industry using a woody feedstock value as high as $46 per dry tonne (Biomass Research and Development Board, 2009). As stumpage prices increase, economic viability of SRWCs will improve. However, reported production costs of SRWCs are high (Tyner et al., 2010) and some have noted that unless crude oil gets much higher, those prices will create a ceiling that will make most feedstocks including SRWCs too expensive to produce for a viable U.S. biofuels industry (Miranowski and Rosburg, 2012). Low oil prices are expected to reduce costs of SRWCs by reducing harvesting and transport costs. Heating oils and wood pellets have the same cost per unit energy at oil price of $55 per barrel, below which stumpage values will fall as there is no floor under the stumpage prices. Although, lower demand and high supply of oil has reduced oil prices currently, it is reasonable to expect a $70-per-barrel

Table 3
Results of economic analyses of the stands using TMS average south-wide stumpage value ($ 11.16 per green tonne) and stumpage values required to break-even under the current stand productivity levels.

Economic metric	Age (yrs.)	Discount rate	Aberdeen	Edenton		Elizabeth City	Garner					Johnston county	Mount Olive	Nash county
			Pop	*Po*	*Ls*	*Pop*	*Fp* (19 yrs)	*Fp* (20 yrs)	*Ls*	*Po*	*Td*	*Pt*	*Po*	*Pop*
NPV ($ ha^{-1})	Actual	3%	−193	−458	−1552	−755	−242	−401	−758	−718	424	210	−532	−175
	10		–	620	−870	−319	–	–	–	–	–	1105	107	−175
	12		–	880	−595	−108	–	–	–	–	–	1474	543	47
	15		−193	1374	−253	162	–	–	–	–	–	1941	1108	331
	18		76	1700	14	379	–	–	–	–	–	2316	1561	562
	20		229	1872	155	498	–	−401	−758	−718	424	2521	1813	691
	Actual	5%	−298	−597	−1665	−743	−734	−819	−1095	−1010	−268	148	−532	−242
	10		–	125	−1223	−414	–	–	–	–	–	818	−50	−242
	12		–	228	−1079	−274	–	–	–	–	–	1054	252	−88
	15		−298	474	−937	−117	–	–	–	–	–	1312	600	87
	18		−137	560	−867	−15	–	–	–	–	–	1477	830	205
	20		−57	579	−851	29	–	−819	−1095	−1010	−268	1545	925	259
IRR (%)	Actual	–	[a]NA	[a]NA	[a]NA	[a]NA	2.19	1.73	[a]NA	[a]NA	4.1	12.67	[a]NA	[a]NA
	10		–	5.61	[a]NA	[a]NA	–	–	–	–	–	19.96	4.3	[a]NA
	12		–	5.89	1.24	2	–	–	–	–	–	19.47	7.49	3.62
	15		[a]NA	6.48	2.43	4.06	–	–	–	–	–	18.09	9.13	5.95
	18		3.61	6.45	3.03	4.91	–	–	–	–	–	16.64	9.41	6.74
	20		4.52	6.35	3.25	5.17	–	1.73	[a]NA	[a]NA	4.1	15.75	9.33	6.92
Stumpage values required to break-even ($ t^{-1})	Actual	3%	15.78	14.37	22.56	61.27	12.67	14.23	18.06	18.62	–	6.12	40.84	13.76
	10		–	–	15.47	16.74	–	–	–	–	–	–	–	13.76
	12		–	–	13.76	12.56	–	–	–	–	–	–	–	–
	15		15.78	–	12.13	–	–	–	–	–	–	–	–	–
	18		–	–	–	–	–	–	–	–	–	–	–	–
	20		–	–	–	–	12.67	14.23	18.06	18.62	–	–	–	–
	Actual	5%	20.71	15.85	25.67	61.56	17.98	20.56	26.06	26.85	13.14	6.49	54.83	19.02
	10		–	–	18.65	20.11	–	–	–	–	–	–	11.93	19.02
	12		–	–	17.24	15.71	–	–	–	–	–	–	–	13.06
	15		20.71	–	16.04	12.7	–	–	–	–	–	–	–	–
	18		14.04	–	15.52	11.33	–	–	–	–	–	–	–	–
	20		12.18	–	15.41	–	17.98	20.56	26.06	26.85	13.14	–	–	–

[a] NA shows IRR values less than or equal to zero.

minimum oil price to be set at which heating oils would be costlier (FutureMetrics, 2014; Simet, 2014).

Our sampled stands were not established with the objective of high productivity rates, and improved growth rates of SRWCs should provide improved economic results but may not reduce production costs enough to make SRWCs economically viable (Miranowski and Rosburg, 2012). It is reasonable to expect feedstock stumpage prices to increase as robust markets develop, which is particularly important at lower stumpage prices (Buchholz and Volk, 2011). A significant effort in that aspect is that EU is working on providing stable market environments for bioenergy by setting mandatory bioenergy targets and polices conducive for investment decisions (Fouquet, 2013). At present, however, price-demand relationships for bioenergy stumpages are not established (Abt et al., 2012) and demand is not elastic to prices. Between second quarters of 2012 and 2013, for instance, U.S. South pulpwood pine demand increased by 3.7% and stumpage prices by 10%, and hardwood stumpage price increased by 10.4% while demand was 2% lower (Forest2Market, 2013). Hence, it is difficult to predict when to expect higher stumpage prices or manage prices by regulating production or harvests. Stumpage values are affected by wood pellet prices in Europe, which are dictated mainly by U.S. bioenergy policies, political drivers in Europe, supply and costs of alternative raw materials of pellets and costs of alternative energy sources. More pellet plants are expected in southeastern U.S. where pellet production is less costly due to lower costs of feedstock and transport.

4. Conclusions

Our study showed irrigation and coppicing can improve biomass productivity of managed hardwood stands on marginal lands. Fertilizer application could also enhance productivity. Rotation length affected productivity and economic outcomes of stands we studied while weed control did not appear to affect productivity. Economic performance of such stands can be improved by minimizing costs and increasing growth rates and stumpage value. These efforts should be accompanied by planting the right species at the right place and for the right rotation length. The fact that younger stands had comparable to higher MAIs when compared to older natural hardwood stands in the southeastern U.S., and that their MAIs are expected to increase with age shows promising productivity potentials of marginal lands. Our findings justify further evaluations of SRWC productivity on marginal lands to meet growing bioenergy demands because worldwide marginal land availability is significant and these lands have the potential to provide sustainable bioenergy feedstock production without the need for using croplands and changing land use.

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Appendix A. Supplementary data

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