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Productivity and profitability potential for non-native *Eucalyptus* plantings in the southern USA

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A B S T R A C T

Renewed interest in non-native *Eucalyptus* species for planting in the southern US has been spurred by projections suggesting they are more productive than the widely cultured *Pinus* species, by warming temperatures, and by attempts to identify frost-tolerant species as well as developing genetically modified *Eucalyptus* for frost tolerance. In addition to questions of environmental suitability, the economic viability of *Eucalyptus* is a significant hurdle to widespread adoption for commercial plantings. We sought to assess the potential obtainable yields and economic feasibility of *Eucalyptus grandis* Hill ex. Maiden and *E. benthamii* Maiden et Cambage, two species suitable for the southern United States. Using the process-based growth model 3PG, we projected potential yields at the sub-county level for *E. grandis* in Florida where it is operationally grown and *E. benthamii* in USDA Plant Hardiness Zones 8a and 8b where it has shown tolerance to occasional low temperatures. The 3PG model estimated mean annual volume increment, inside bark (MAI) that was used to estimate land expectation value (LEV) and internal rate of return (IRR).

The MAI of *E. grandis* ranged from 18 to 119 m^3 $ha^{-1}year^{-1}$ (9 to 59.5 dry Mg ha^{-1} $year^{-1}$) with a mean of 42.6 m^3 $ha^{-1}year^{-1}$ (20.8 dry Mg ha^{-1} $year^{-1}$) for sites in peninsular Florida. The lower growth projections came from north Florida areas where annual frosts occur. Excluding urban areas, the LEV of *E. grandis* ranged from $-1264 to $1710 ha^{-1} with a mean of $424 ha^{-1}. The estimated IRR ranged from −9.7% to 16.9% with a mean of 8.2%. *Eucalyptus benthamii* MAI ranged from 3.3 to 76 m^3 $ha^{-1}year^{-1}$ (1.8 to 41.8 Mg $ha^{-1}year^{-1}$), with a mean of 21.9 m^3 $ha^{-1}year^{-1}$ (11.9 Mg $ha^{-1}year^{-1}$). The higher yields were primarily located in coastal regions of USDA Plant Hardiness Zone 8b. Excluding urban areas, LEV ranged from $-2707 ha^{-1} to $1532 ha^{-1}. The maximum estimated IRR was 15.9%. Our results show that *Eucalyptus* is potentially profitable as a bioenergy crop in the southern USA, but potential profitability of *E. benthamii* was limited by low temperature; positive LEV was obtained where productivity was 30 m^3 $ha^{-1}year^{-1}$ or more. Profitability was restricted to a small percentage (12%) of sites theoretically within the operational range in the southern U.S. indicating that a wholesale conversion of *Pinus taeda* plantations is unlikely.

1. Introduction

Increasing interest in developing dedicated short-rotation bioenergy plantations in the southern United States has focused on a limited number of fast-growing trees including *Eucalyptus* species (Perlack et al., 2011). Many *Eucalyptus* species have desirable properties for bioenergy plantations, including rapid growth, ability to coppice, and high wood density. Their indeterminant growth pattern and evergreen foliage allows eucalypts to grow while climatic conditions are suitable and their sclerophyllous leaves allow them to withstand very dry conditions. The major commercial *Eucalyptus* species, however, are intolerant of low temperatures, limiting plantings in the US to frost-free

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regions of Florida, California and Hawaii. *Eucalyptus* species were introduced into the southern US as early as 1878, but it was not until the late 1960s before commercial plantations were established (Kellison et al., 2013). Beginning in 1959 the Hardwood Research Cooperative at North Carolina State University began species-introduction trials that eventually tested 569 sources representing 103 species. Interest declined, however, after severe winter temperatures in late 1983 and early 1984 and 1985 caused significant mortality (Kellison et al., 2013) but genetic improvement continued in tropical Florida (Rockwood, 2012).

Eucalyptus spp. again are in the forefront as temperatures in the southern US have warmed, accompanied by renewed effort to identify frost-tolerant species as well as using biotechnology to genetically modify *E. grandis* for increased frost tolerance. Assuming that frost-tolerant species and genotypes can be identified, an estimated 5000 to 10,000 ha $year^{-1}$ of commercial *Eucalyptus* plantations could be established in the South (Dougherty and Wright, 2012) and release of a clone genetically modified for freeze tolerance could potentially replace up to 1.13 million hectares of naturally regenerated and plantation *Pinus* spp. (Wear et al., 2015). Projections suggest that short-rotation *Eucalyptus* spp. are significantly more productive than the widely cultured *Pinus* species in the southern USA (Hinchee et al., 2009; Gonzalez et al., 2011; Zalesny et al., 2011). The species/cultivars/hybrids with greatest potential for bioenergy in the Southeast are being evaluated at 13 sites from Texas to North Carolina (Zalesny et al., 2011). It is likely that SRWC will be part of the long-term bioenergy solution in the U.S. (Stanturf et al., 2003; Hinchee et al., 2009; Perlack et al., 2011; Zalesny et al., 2011; Kellison et al., 2013). Unlike other potential bioenergy species that include *Pinus taeda* L. and *Populus* spp., *Eucalyptus* spp. are not native to the USA and questions abound as to their effects on biodiversity, wildfire risk, and water resources (Stanturf et al., 2013). In addition to questions of environmental suitability, economic viability of commercial SRWC plantings is a significant hurdle to widespread adoption of *Eucalyptus* spp. The objective of this study was to assess the potential obtainable yields and economic feasibility of *Eucalyptus grandis* Hill ex. Maiden and *E. benthamii* Maiden et Cambage, two species suitable for the southern United States. Our approach was to apply a process-based growth model, 3PG (Landsberg and Waring, 1997) to site and climatic conditions in a geospatial context and to evaluate modeled biomass yields (mean annual increment, MAI) by the economic criteria of land expectation value (LEV) and internal rate of return (IRR). Our modeled results are visualized at the 5-digit ZIP Code Tabulation Area level (ZCTA), which are generalized areal representations of United States Postal Service delivery areas and generally are smaller than political subdivisions such as counties. The results can be used to analyze feasibility of current or proposed bioenergy projects as well as to assess the potential environmental implications of widespread deployment of a non-native plant.

2. Methods

2.1. Species and site characteristics

2.1.1. Eucalyptus grandis

Eucalyptus grandis is not native to the United States and its potential operable range is limited by a lack of frost tolerance. Rockwood (2012) provided a current planting map in the southern USA, showing the operable range as limited to the northeast, central and southern portions of Florida (Fig. 1). *Eucalyptus grandis* exhibits indeterminate growth and does not set a bud or become dormant. It is capable of building high levels of leaf area given adequate resources. With competition control and nutrition management to promote vigor, *E. grandis* sprouts readily although reduced coppicing ability has been reported after summer harvests (June–September) in Florida (Meskimen and Francis, 1990). *Eucalyptus grandis* and *Eucalyptus grandis* × *E. urophylla* hybrids are managed on coppice rotations in multiple areas around the globe for the production of pulpwood, charcoal, and fuelwood. The best growing conditions for *E. grandis* are comprised of zero frost days, high levels of incoming radiation, and large amounts of annual precipitation. *E. grandis* is capable of growing through the divided wet-dry season weather regime characteristic of the southern peninsula of Florida where an extended dry period in the winter months of November through March is followed by a wet season that typically begins in late May and continues through early autumn.

E. grandis is capable of vigorous growth on a range of soils; Kellison et al. (2013) suggested concentrating efforts on soils of sandy clay loam and clay loam textures and avoiding soils with imperfect or excessive drainage. Much of southern Florida, where the species is currently grown, is characterized by oceanic sand deposits and a sand-based central ridge. Farther south and in areas away from the central ridge, soils are mostly poorly to very poorly drained and of low fertility. To reach full growth rate potential, nutrient amendments are needed on all soils in this region.

Rockwood (2012) reviewed the history and status of *Eucalyptus grandis* tree improvement in Florida. Options and availability of planting material currently are limited. Five commercial varietal lines have been released by the University of Florida and are available from commercial nurseries. Lykes Brothers Ranch in Glades County, FL is the oldest commercial *Eucalyptus* operation and they developed a "Lykes-race" brand of *E. grandis* seed. The variety *E. urophylla* × *E. grandis* (EH1) has been planted at multiple sites in south Florida by ArborGen LLC (http://www.arborgen.com/) and additional clones from Brazil are being tested for potential deployment.

As a result of continued genetic improvement, most *E. grandis* stands are only coppiced for one or two rotations before re-establishment with improved clones. Harvest cycles of five to seven years are typical for pulpwood or charcoal production. Due to the high leaf area production and subsequent growth potential, nutrient demands are high. Fertilization regimes typically include a starter fertilizer and one or more follow-up applications. With appropriate site preparation and control of competing vegetation, *E. grandis* early growth is rapid and sites are quickly occupied. Planting densities for bioenergy range from 1482 to 3212 stems $hectare^{-1}$. Row spacing is generally 3 m to 3.7 m between rows. Within-row spacing generally ranges from 0.9 m to 1.8 m between trees (Wright et al., 2010; Dougherty and Wright, 2012).

2.1.2. Eucalyptus benthamii

Eucalyptus benthamii is currently planted operationally and shows promise for hardwood pulpwood or bioenergy feedstocks. The species was not included in the species trials completed in the early 1980s (Kellison et al., 2013) and only limited research on *E. benthamii* has been completed (Stape et al., 2011). MeadWestvaco has made substantial plantings in eastern Texas and western Louisiana (Zalesny et al., 2011). The potential operable range is known to be limited by cold tolerance. For this modeling project, the range was considered to include historical USDA Plant Hardiness Zones 8A and 8B (Fig. 2). Originally the range was thought to be at or below the Zone 8b boundary, but survival through the winters of 2010 and 2011 was well north of those previously defined ranges in species screening trials conducted by the Forest Productivity Cooperative (Region Wide 24). Nevertheless, during the same period *E. benthamii* experienced substantial damage that would affect growth below the boundary of zone 8b (Butnor et al., 2018).

Similar to *E. grandis, E. benthamii* has a sustained growth period and does not set a bud. It does acclimate to colder weather by hardening of the leaf and stem tissues, thereby achieving some frost tolerance. Subjected to a string of warm days, growth begins anew and a warming trend in the winter followed by a quick cold snap with below freezing temperatures can cause foliage and stem damage or mortality. Winter temperatures in Hardiness Zones 8A and 8B stay cool enough to maintain winter dormancy while avoiding warmer spells. *E. benthamii* sprouts vigorously and can be managed under a coppice regime. At

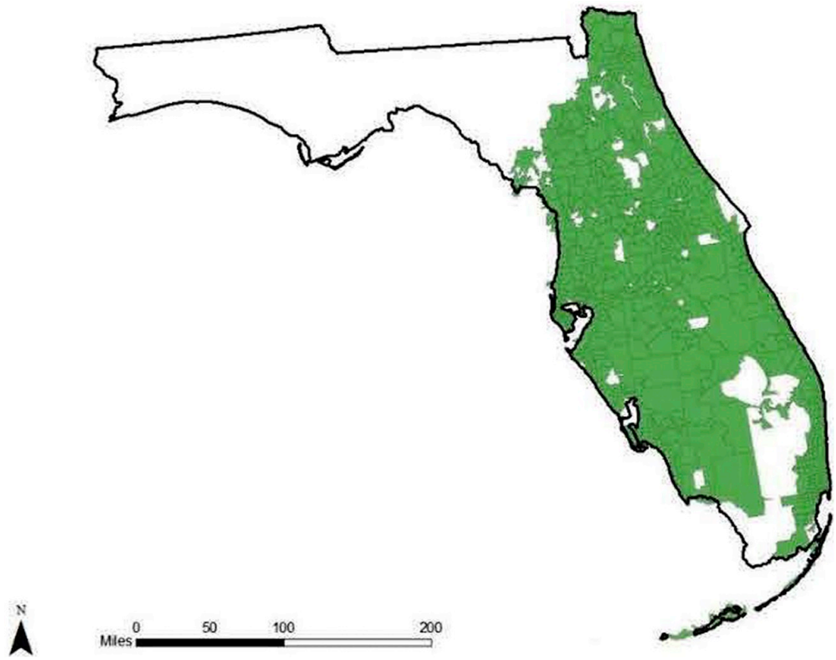

Fig. 1. *Eucalyptus grandis* operable range in peninsular Florida (based on Rockwood, 2012).

present, *E. benthamii* container seedlings are commercially available from ArborGen, LLC in Ridgeville, SC (http://supertreeseedlings.com/wp-content/uploads/2016/05/eucalyptus-product-sheet.pdf).

2.2. Growth model

The process-based 3PG model (Landsberg and Waring, 1997; Landsberg et al., 2003) estimates gross primary productivity (GPP) of a species and then allocates that growth to various parts (roots, boles, branches, and leaves). The 3PG model has been used successfully to model *Eucalyptus globulus* in Tasmania (Landsberg and Waring, 1997; Sands and Landsberg, 2002) and *E. grandis* and hybrids in Australia, South Africa (Dye et al., 2004) and Brazil (Almeida et al., 2004). Because 3PG predicts growth based on species traits and given climate, environmental, and growing site conditions, it can be used to accurately predict growth potential where a species had not previously been planted (Almeida et al., 2004). We used the 3PG model to develop growth potential expressed as mean annual volume increment (MAI) for each 5-digit ZCTA in the ranges of *E. grandis* and *E. benthamii*.

Approximately 42 inputs are required to run the model. Some of the variables are general constants or defaults typical of trees in general. Of the parameters that are species dependent, canopy structure and process variables (specific leaf area, extinction coefficient for photosynthetically-active radiation absorption, age of full canopy cover, canopy quantum efficiency, and proportion of rainfall intercepted by canopy) determine light capture, light use, and precipitation interception. Gross primary productivity is calculated as a function of absorbed photosynthetically-active radiation (APAR) and the species effective canopy quantum efficiency (QE, carbon produced per unit of light intercepted). The effective QE is calculated by constraining the maximum

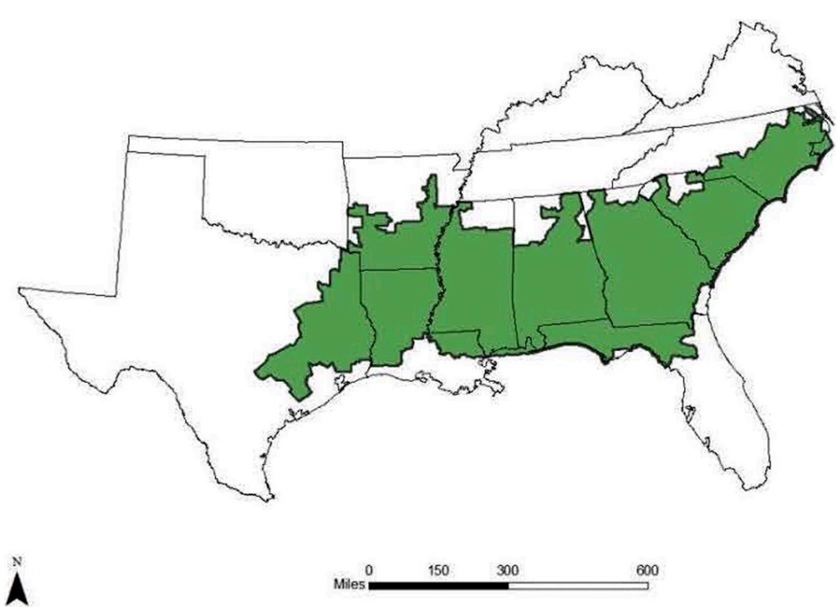

Fig. 2. Modeled range of *Eucalyptus benthamii* (USDA Plant Hardiness Zones 8a and 8b).

possible QE by the effect of the vapor pressure deficit (VPD) on stomatal conductance and therefore carbon (C) captured and water transpired. Net primary productivity (NPP) is estimated from a constant ratio of GPP to NPP, and thus respiration is not tracked or accounted for directly. Internal equations allocate NPP to the several tree components (bole, branches, and leaves, coarse and fine roots). The portion of NPP allocated to the roots is influenced by moisture relations and soil nutrition. Allocations of NPP to stems and foliage are a function of the ratio of weight of foliage:dbh to the weight of stem:dbh. Foliage weight is impacted by soil nutrition, which is indexed by a fertility rating (FR) ranging from 0 to 1. Carbohydrate calculations are conducted on a single tree basis. Initial stand level stocking is a user-selected variable and survival is calculated using the self-thinning law. Litter fall and root turnover are calculated monthly.

For the parameters specific to *Eucalyptus*, we relied on the values developed by of Dye et al. (2004) for *E. grandis* × *camaldulensis* in South Africa. We compared their model to two others developed in Brazil; one was developed for *E. grandis* (Almeida et al., 2004) and the other for *E. grandis* × *urophylla* (Stape et al., 2004; Almeida et al., 2010). We ran all three models using weather data from Florida and the Dye et al. (2004) parameterization gave results that best matched observed growth; results of the other two models were unrealistically high compared to literature and operational yields. We used the same parameterization for both *E. grandis* and *E. benthamii* except for the frost modifier, specific leaf area, and wood density.

Frost damage to eucalypts ranges from stem or top dieback to complete mortality. The 3PG model includes frost variables and modifiers that affect how monthly NPP is allocated. A cold event may delay growth for a few days of dormancy or damage the leaves and reduce leaf area for an extended period. Frosts are infrequent in most of the operational range of *E. grandis* but they do occur, especially in north Florida, and the species is sensitive to frost; therefore, we used a modifier of 5 days of production loss for each frost day. For the less sensitive *E. benthamii*, the frost modifier was set at 3 days per frost event. The effect depends on the severity of the freeze event and the age and hardiness of the plant cells present. Estimates of potential thresholds for foliage damage to *E. benthamii* by age (Table 1) are based on observed damage in stands in South Carolina, Georgia, Alabama, Louisiana, and Texas (Wright et al., 2010) and the mortality threshold is based on observations in South Carolina (Dougherty and Wright, 2012).

The value for specific leaf area (SLA) used for *E. grandis* was 7.5 $m^2 kg^{-1}$, based on Dye et al. (2004). A higher value was used for *E. benthamii*, 9.1 $m^2 kg^{-1}$, based on destructive sampling of 3-year-old trees near Fargo, GA (Dougherty, *unpublished*). A higher value for wood density was used for *E. benthamii* than *E. grandis*, respectively 0.55 and 0.5 $g cm^{-3}$ (Pirraglia et al., 2011).

2.2.1. Initialization inputs

The 3PG growth model uses initialization inputs to describe site-specific values including latitude, establishment dates, soil texture class, fertility effect, initial available soil water, maximum and minimum available soil water, stocking, and initial weight of foliage, stem, and root biomass. To simplify inputs into 3PG, we developed a matrix of soil texture classes (sand, sandy loam, clay loam, and clay) and associated fertility and soil water availability. The matrix was further divided into upland and lowland sites to represent differences in soil drainage; upland sites are moderately well- to exceptionally well-drained and lowland sites are somewhat poorly-, poorly-, and very poorly-drained. To capture the range of productivity potential, we added fertility and available soil water to the matrix (Table 2). The fertility rating is an index ranging from 0 to 1 where a rating of "1" implies very high nutrient availability and "0" frames the low end of available nutrition. The inherent fertility rating is based largely on how soil texture and soil organic matter affect soil N (and secondarily P) supplying capacity and retention capacity. 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
Estimate of minimum temperature thresholds at or below which foliage damage or mortality may occur in *Eucalyptus benthamii* stands in the southern USA.

	Foliar damage	Survival
Age	Minimum temperature	Minimum temperature
1	−3.9 °C	−11.0 °C
2	−3.9 °C	−11.7 °C
3	−5.0 °C	−12.8 °C
4	−9.5 °C	−11.0 °C

Table 2
Fertility rating, fertilizer response, minimum and maximum available soil water in terms of eight soil texture and site position combinations.

Soil texture	Site position	Fertility[a] rating	Fertilizer[b] response	Minimum[c] available soil water	Maximum[c] available soil water
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] Index of inherent soil fertility; 1 = high fertility, 0 = low fertility.
[b] Index of responsiveness to added nutrients that depends on ability to add leaf area.
[c] Available soil water in mm H_20 m^{-1} soil depth.

The response to fertilization depends on the inherent or manipulated level of soil fertility. The basic principle is that growth response across soil types depends on the ability to produce more leaf area for light interception. On soils with high inherent fertility, leaf area levels are already high and added nutrients will not increase light capture further. Alternatively, soils with inherently low nutrient levels can see major responses in productivity from fertilization because there is room to grow additional leaves for light capture. Fertilizer response is included in the soil matrix used for the 3PG model (Table 2).

We modeled productivity spatially for each US Census Bureau 5-digit ZIP Code Tabulation Area (ZCTA) in the operational ranges of *E. grandis* and *E. benthamii*. We used the US ZCTA boundary map (https://www.census.gov/geo/reference/zctas.htmlaccessed; last accessed 12 February 2016) to combine soil map units within each ZCTA; the dominant texture class was assigned to ZCTA using the spatial overlay feature of ArcGIS©. Tabular and spatial data for soil series were collected from USDA Natural Resources Conservation Service (2012) SSURGO database at the county level (http://sdmdataaccess.nrcs.usda.gov/ last accessed July 12, 2015).

Weather data required to run the model included frost days, precipitation, and minimum and maximum temperature. Monthly average data from individual weather stations were 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). Stations with incomplete records were excluded; for the 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

Table 3
Management practices and related costs for *Eucalyptus grandis and E. benthamii.*

Year[a]	Activity	Cost ha^{-1}
0	Spot raking	$ 99
0	Chemical Site Prep /Vegetation removal	$161
0	Single pass bed	$210
0	Weeding	$ 86
0	Planting (1730 stems ha^{-1})	$605
1	Weeding	$124
1	Nitrogen Fertilizer (45 kg ha^{-1})	$ 96
2	Nitrogen Fertilizer (179 kg ha^{-1})	$388
4	Nitrogen Fertilizer (224 kg ha^{-1})	$484
5	Harvest[b]	
0	Shearing (after each harvest)	$222

[a] Indicates the year of each rotation.
[b] Harvesting occurs at ages 5, 10, and 15.

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 each weather variable.

2.2.2. Silvicultural regime

Users can select silvicultural variables and regimes for the model. Regimes include irrigation, fertilization, thinning, and coppice; irrigation was regarded as too costly and thinning was unnecessary under coppice management. Other values represent the genetics of the species, expected defoliation rates, and a ranking for competition from weeds. We used 1730 stems $hectare^{-1}$ in the model, at the low end of the recommended planting densities for biomass for both *Eucalyptus* species of 1482–3212 stems hectare $^{-1}$ (Wright, 2010; Dougherty and Wright, 2012). Due to the high leaf area production and growth potential, nutrient demands are high. Operational fertilization regimes typically include a starter fertilizer and one or more follow-up applications. Nutrient additions were modeled to be applied in years 0, 1, and 4. Fertilization rates and other management activities and their costs are given in Table 3.

Both *E. grandis* and *E. benthamii* have the ability to coppice; production increases in the initial coppice rotation and decreases in the second coppice stand because mortality increases. The productivity of a coppice rotation depends on both coppice vigor and survival. The amount of stored energy in the root system determines the growth of subsequent coppice stands and the stored energy depends on the size of the stump, the vigor of the harvested plant, and the internal allocation of carbohydrates at the time of harvest. Survival of an individual stump depends on the energy available for growth and any negative effects of disease, stump damage, weather, and animal or insect attack. We modeled a harvest cycle of 5 years for both species with two coppice rotations following the initial planting. The yield of the first coppice was assumed to increase to 115% of the initial harvest. The yield of the second coppice was assumed to decline to 80% of the first coppice yield (or 92% of the initial harvest yield).

2.2.3. Validation

Models are usually validated using data from one site and comparing results to data from another site, thus validation is at the stand level. Because we were modeling growth at the regional level, site-level validation was impossible because of lack of data for the many sites of interest. Hence, validation of the model for the operational regions was based on comparison to the range of published and observed data from multiple sites rather than to observed data from an individual site. Wright et al. (2010) reported mean annual increment yield from a seven-year-old stand of EH1 (*E. grandis* × *urophylla*) in Sebring, Florida as 78.5 green Mg ha^{-1} $year^{-1}$. Dickens et al. (2011) summarized the potential of *E. grandis* at high fertilization and high stocking in the range of 22.9 to 71.5 green Mg ha^{-1} $year^{-1}$ (stemwood + branches + foliage) based on a study near Orlando, Florida. Wright et al. (2010) summarized yield data from a literature review of *Eucalyptus* plantings; yields were in the range of 11 to 27.8 dry Mg ha^{-1} $year^{-1}$. Average yields of *E. benthamii* are predicted to be 27 to 36 dry Mg ha^{-1} $year^{-1}$ on a 7-year rotation based on ArborGen and MeadWestvaco internal data (Zalesny et al., 2011).

2.3. Economic model

Although a variety of 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. This method discounts all costs and benefits over a rotation or a planning horizon to a reference time, i.e., it is the present value of future revenues minus the present value of future costs. The internal rate of return (IRR) of an investment is the discount rate at which the NPV equals zero. The higher a site's IRR, the more desirable it is to plant the specific SRWC species on the site. The land expectation value (LEV) is used to correctly consider the opportunity cost of capital and land and determine optimal forest management practices (Chang, 1998); LEV is the NPV of bare land assuming a perpetual land management regime. Medema and Lyon (1985) developed the analytical method for evaluating coppicing regimes that was used by Langholtz et al. (2005) to investigate the effect of a dendro-remediation incentive on the LEV of *Eucalyptus grandis* coppice systems in Florida. Similarly, Langholtz et al. (2007) evaluated the LEV of growing *Eucalyptus amplifolia* on phosphate mined lands using the same model. Instead of incorporating the stages of coppice system into the equation as Langholtz et al. (2007) suggested, we used the basic Faustmann model to calculate the LEVs of *Eucalyptus* plantations. It defines net returns as the sum of the present value benefits less the sum of the present costs per rotation in perpetuity:

$$LEV = \frac{\sum_{i=0}^{t} V_{(biomass)i}e^{-rt} - \sum_{i=0}^{t} C_i e^{-rt}}{1 - e^{-rt}} \quad (1)$$

where $V_{(biomass)i}$ is the value of biomass at time i (i.e., stumpage price times yield), C_i the stand establishment cost and management cost incurred at time i, r the real discount rate, and t the rotation age. We modeled a harvest cycle of 5 years with two coppice rotations following the initial planting. Therefore, the rotation age t is 15. For the revenue and management costs incurred in the second and third coppice, the time i ranges from years 6–10 and years 11–15.

To evaluate LEV and IRR of *Eucalyptus* species, we used the 3PG model to project growth at each ZCTA. Inputs to the economic model included the mean annual increment (MAI) from the 3PG model, costs for site preparation, planting, and fertilization, stumpage price, and a discount rate. Rotation length, number of coppice rotations, and the ratios of initial and subsequent coppice harvests were fixed for each species based on previous research. The models converted 3PG outputs, MAI of the volume inside bark yield (m^3 ha^{-1} $year^{-1}$), to dry weight of biomass using the specific volume to weight conversion factors (0.5 dry Mg m^{-3} for *E. grandis* and 0.55 dry Mg m^{-3} for *E. benthamii*).

The harvest yield was the product of MAI of biomass weight and stand age. The initial harvest and coppice harvests were percentages of the product, depending on species, planting density, etc. Considering that the biomass yield is inside-bark, the stumpage price was assumed to be $10 Mg^{-1} for all species, slightly higher than Timber-Mart South (http://www.timbermart-south.com/) pulpwood prices. The LEV was calculated using an annual discount rate of 5%. The IRR was calculated using the cash flow of costs and revenues of the total rotation.

2.4. Visualization

All 3PG model yield and economic model results were spatially organized at the 5-digit ZCTA level using GIS methods. Two sets of

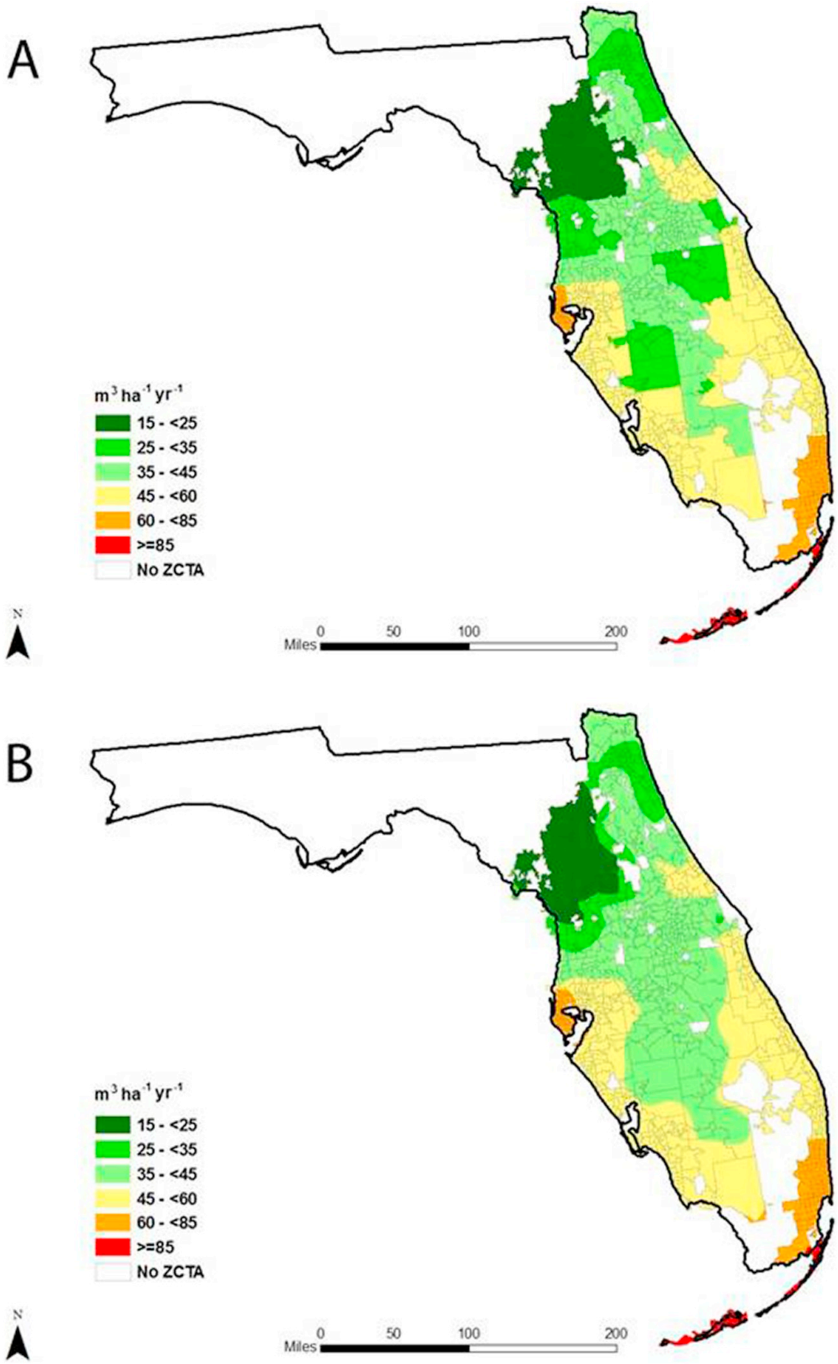

Fig. 3. The yield of *Eucalyptus grandis,* mean annual increment (MAI) at age 5 in $m^3\,ha^{-1}\,year^{-1}$ estimated as volume inside bark: *(a)* MAI at the 5-digit ZCTA level; (b) MAI smoothed by Simple Kriging.

maps were produced: one set was based on the estimated values from 3PG model yield outputs and economic model outputs and the second set used a spatial interpolation technique (Simple Kriging) to avoid the influence of political boundaries and illustrate the general spatial patterns of biomass yield and economic value from the modeling (Oliver and Webster, 1990).

To better visualize results, we used Simple Kriging and ArcGIS® to generate a smooth predictive output map from modeled data at known locations. This spatial interpolation technique smoothes the rigid shapes reflected in artificial administrative boundaries. The kriging method assumed that the distance or direction between known points reflected a spatial correlation that can be used to explain variation in the surface. It uses a weighted moving average interpolation to produce the optimal spatial linear prediction (Oliver and Webster, 1990).

3. Results

3.1. Biomass

Mean annual volume increment of *E. grandis* ranged from 18 to 119 $m^3\,ha^{-1}\,year^{-1}$ (9 to 59.5 dry Mg $ha^{-1}\,year^{-1}$) with a mean of 42.6 $m^3\,ha^{-1}\,year^{-1}$ (21.3 dry Mg $ha^{-1}\,year^{-1}$). These values are within the range of 11 to 36 dry Mg $ha^{-1}\,year^{-1}$ used to validate the model (Dickens et al., 2011; Wright et al., 2010; Zalesny et al. 2010) with the exception of our high estimate from extreme south Florida. The lower end of the output range comes from areas in north Florida

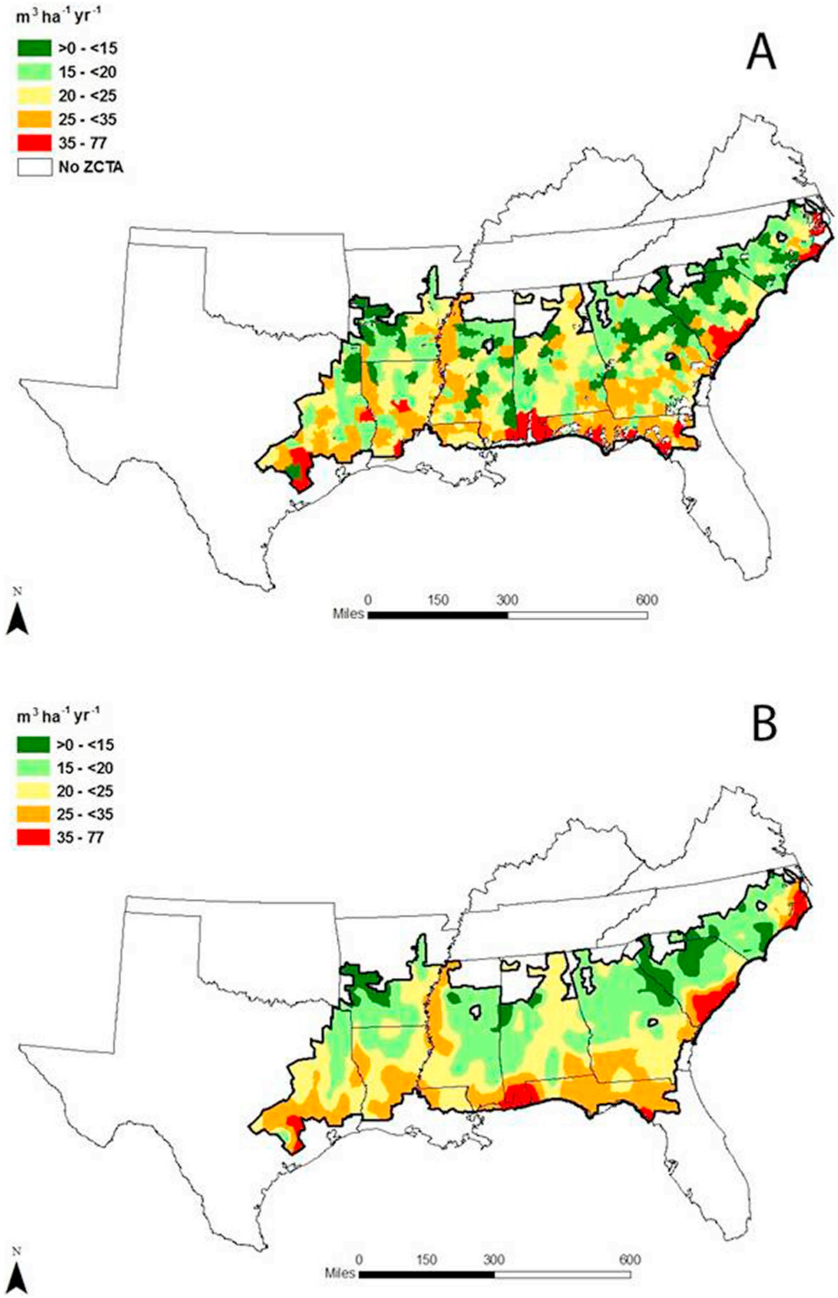

Fig. 4. The yield of *Eucalypts benthamii,* mean annual increment (MAI) at age 5 in $m^3\,ha^{-1}\,year^{-1}$ estimated as volume inside bark: *(a)* MAI at the 5-digit ZCTA level; (b) MAI smoothed by Simple Kriging.

where annual frost is prevalent. The highest yield estimates are in extreme south Florida and somewhat lower yields are projected on the east and west coasts of south Florida where mean annual volume increment ranges from $45\,m^3\,ha^{-1}\,year^{-1}$ to $119\,m^3\,ha^{-1}\,year^{-1}$ (22.5 to 59.5 dry Mg $ha^{-1}\,year^{-1}$). Lower yield production occurs on the sandy soils of the Central Florida Ridge (Fig. 3).

Projected MAI values for *E. benthamii* from the five-year modeled regime ranged from 3.3 to $76\,m^3\,ha^{-1}\,year^{-1}$ (1.8 to $41.8\,Mg\,ha^{-1}\,year^{-1}$), with a mean of $21.9\,m^3\,ha^{-1}\,year^{-1}$ ($11.9\,Mg\,ha^{-1}\,year^{-1}$; Fig. 4). The higher yields were primarily located in coastal regions of USDA Plant Hardiness Zone 8b, extending landward in Texas (TX), Louisiana (LA), and Mississippi (MS). The east coast of North Carolina, southeast coast of South Carolina, and the Florida Panhandle (Escambia) have the highest yield production ranging from $35\,m^3\,ha^{-1}\,year^{-1}$ to $76\,m^3\,ha^{-1}\,year^{-1}$ (19.3 to $41.8\,Mg\,ha^{-1}\,year^{-1}$). Yields projected for southwest and south-central Georgia were higher than areas of similar latitude to the west in Alabama (AL). Central South Carolina and west Arkansas have the lowest yield production lower than $15\,m^3\,ha^{-1}\,year^{-1}$ ($8.3\,Mg\,ha^{-1}\,year^{-1}$).

3.2. Potential profitability

Some urbanized and surrounding areas in Florida were excluded because of alternative land use options (Key West, St. Petersburg, Tampa, Hialeah, Ponce Inlet, and Fort Lauderdale). The LEV of *E. grandis* in Florida ranged from \$-1264 to \$1710 ha^{-1} with a mean of \$424 ha^{-1}. The estimated IRR ranged from −9.7% to 16.9% with a mean of 8.2%. South coastal areas had the highest LEV and northern areas the lowest LEVs (Fig. 5). IRR for *E. grandis* has a similar spatial pattern as LEV, except that the area with the lowest IRR values in north

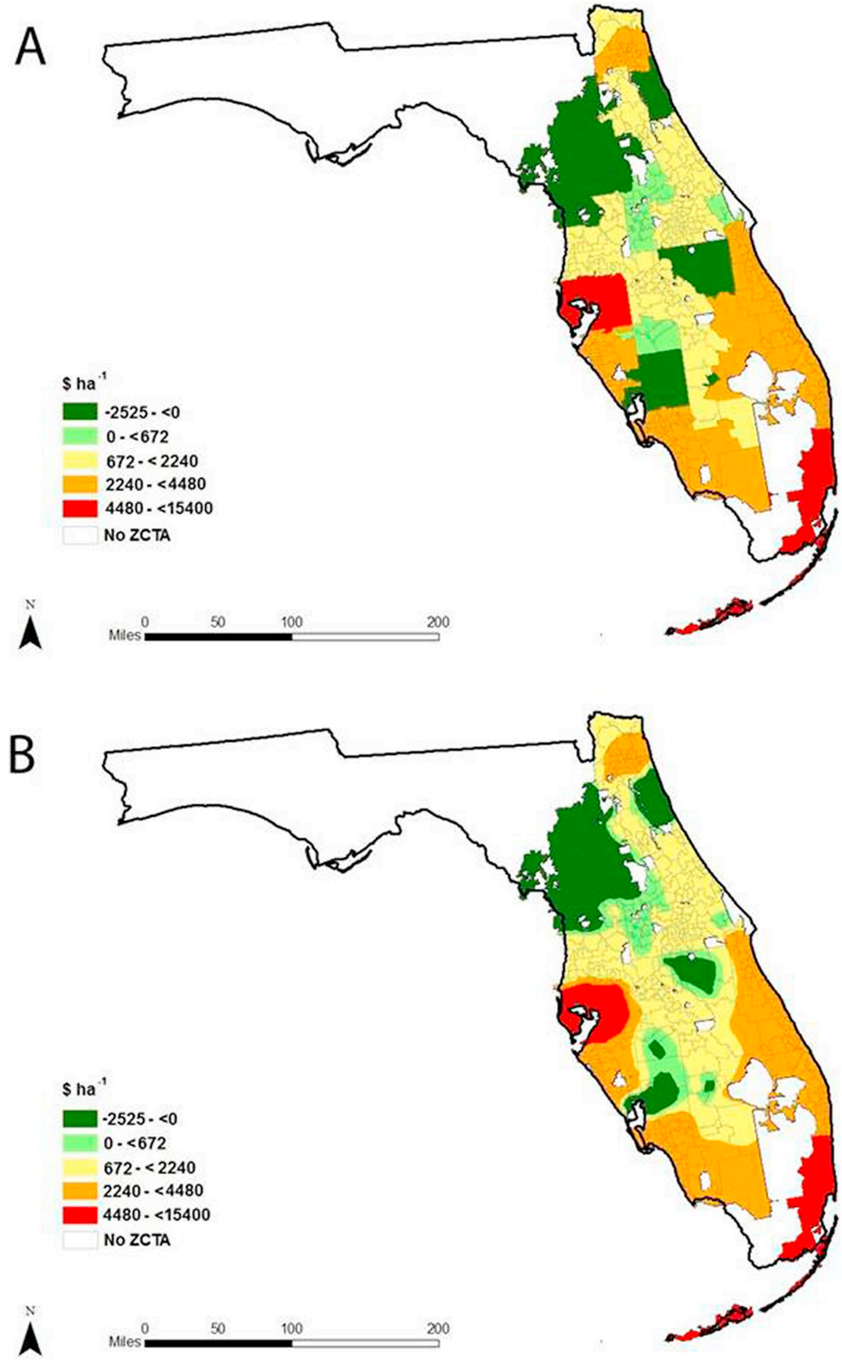

Fig. 5. Land Expectation Value (LEV) of *Eucalyptus grandis* with a 5-year rotation length: (a) LEV at the 5-digit ZCTA level; (b) LEV smoothed by Simple Kriging.

Florida was smaller and the areas in central Florida with higher IRR values were larger (Fig. 6).

Model assumptions for *E. benthamii* were the same as for *E. grandis*; the initial rotation and coppice length (5 years) and total rotation length (15 years) was the same on all sites. The first coppice yield was assumed to increase to 115% of the initial harvest and the second coppice yield would decline to 80% of the first coppice yield (92% of initial harvest). Management practices and related costs for soils in the Southeastern U.S. are shown in Table 3.

Some coastal urban areas were excluded because of alternative land use options, including Charleston in South Carolina, and Panama City and Sea Hag Marina in Florida. Elsewhere, the LEV of *Eucalyptus benthamii* ranged from \$-2707 ha^{-1} to \$1532 ha^{-1} (Fig. 7). A large portion of the Southeast had negative LEV, essentially where MAI was projected at less than 30 $m^3\,ha^{-1}\,year^{-1}$. Profitability of *E. benthamii* was affected by low projected yields because of weather limitation, primarily frost. Profitability was restricted to a small percentage (12%) of sites theoretically within the operational range in the southern U.S. The maximum estimated IRR was 15.9%. The east coast of North Carolina (NC) and southeast coast of South Carolina (SC) have the highest LEV, while the rest of North Carolina and South Carolina, north Georgia (GA), west Alabama (AL), east Mississippi (MS) and south Arkansas (AR) have the lowest LEVs (Fig. 7). IRR has a similar pattern for highest values, but only west North Carolina, north South Carolina and central Georgia display the lowest IRR values (Fig. 8).

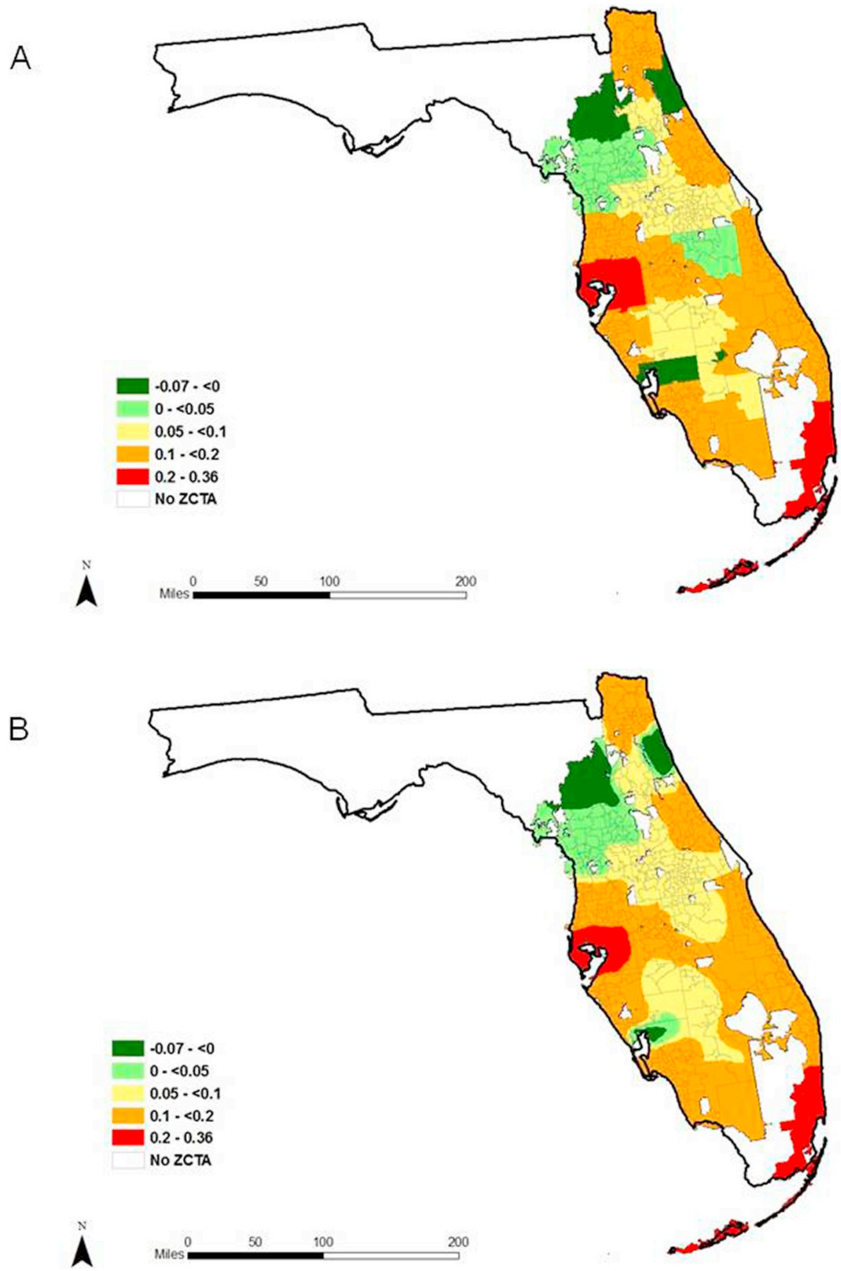

Fig. 6. Internal Rate of Return (IRR) of *Eucalyptus grandis* with a 5-year rotation length: (a) IRR at the 5-digit ZCTA level; (b) IRR smoothed by Simple Kriging.

4. Discussion

Non-native *Eucalyptus* species are potentially more productive than native *Pinus* species on upland sites in the southern USA (Hinchee et al., 2009; Gonzalez et al., 2011; Dougherty and Wright, 2012) and offer an alternative to harvesting native hardwoods forests for pulpwood (Wear et al., 2015). Additionally, selected *Eucalyptus* species have been evaluated for conversion into many products (Rockwood et al., 2008) including ethanol (Daystar et al., 2015) or solid fuel (Junior et al., 2017). Interest in *Eucalyptus* is supported by experience in Florida where *E. grandis* and *E. amplifolia* short rotation systems can produce up to 67 green Mg ha^{-1} $year^{-1}$ in three years (Rockwood, 2012). The renewed interest in the USA in fast growing trees for bioenergy plantations (Perlack et al., 2011) has raised a number of questions as to sustainability (Williams et al., 2009; Vance et al., 2014; Robledo-Abad et al., 2017), carbon neutrality (Marland, 2010; Vanhala et al., 2013) and effects on biodiversity (Immerzeel et al., 2014; Tarr et al., 2017) as well as economic feasibility (McKenney et al., 2014; Ghezehei et al., 2015). The emergence of non-native *Eucalyptus* species as potential bioenergy crops has engendered additional questions including biological feasibility and potential invasiveness (Gordon et al., 2012; Callaham et al., 2013), effects on wildfire behavior (Goodrick and Stanturf, 2012), and water consumption (Vose et al., 2015; Maier et al., 2017).

Questions about the sustainability of biomass plantings generally and for use of non-native *Eucalyptus* specifically need to be discussed in the context of whether dedicated plantings are viable in terms of productivity and economics. We attempted to show, in spatially explicit terms, where two species of *Eucalyptus, E. benthamii* and *E. grandis* would be potentially profitable as bioenergy crops in the southern USA. Using the process-based growth model 3PG, we projected potential yields at the sub-county, 5-digit ZCTA level for *E. grandis* in peninsular Florida where it is operationally grown and *E. benthamii* in USDA Plant Hardiness Zones 8a and 8b where it is thought to be adapted to occasional low temperatures. It should be noted that Hardiness Zone 8b is

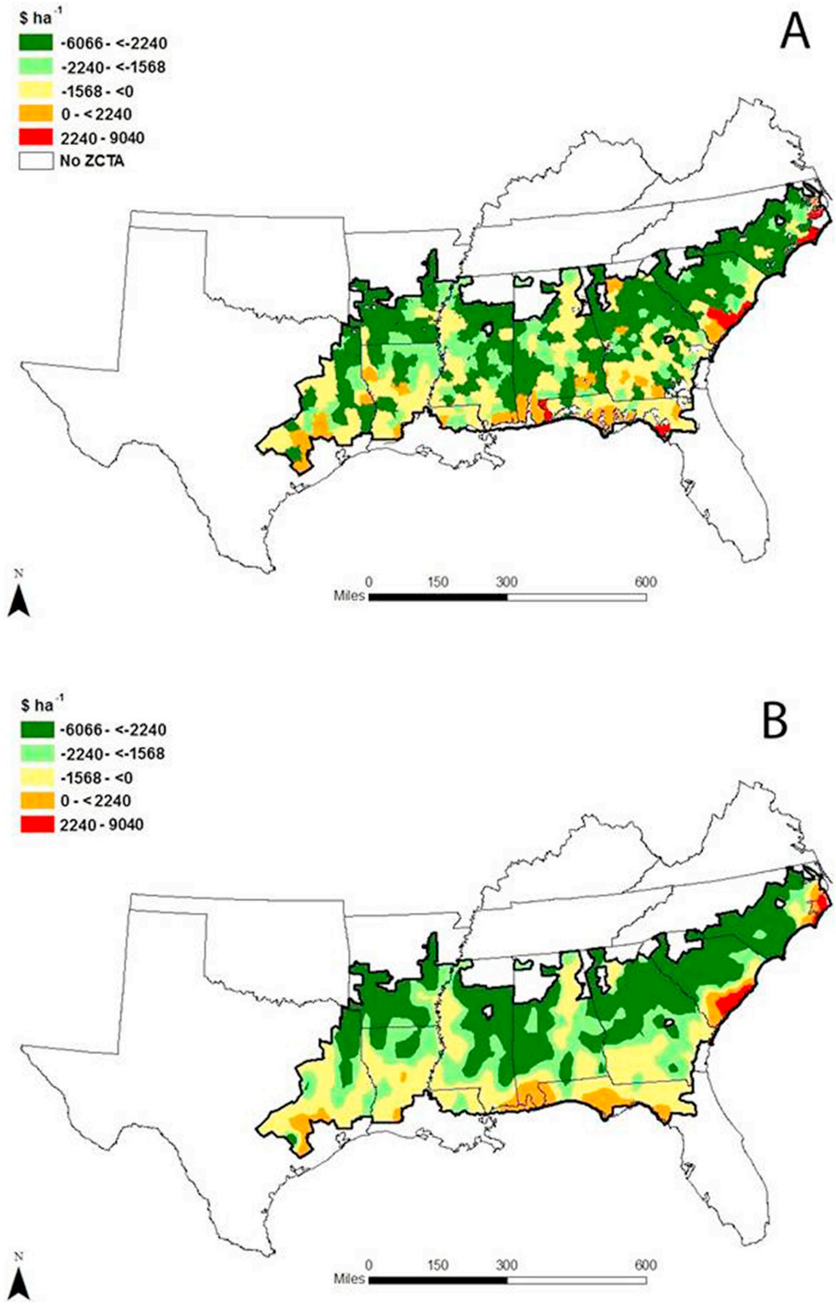

Fig. 7. Land Expectation Value (LEV) of *Eucalyptus benthamii* with a 5-year rotation length*:* (a) LEV at the 5-digit ZCTA level; (b) LEV smoothed by Simple Kriging.

the same area where non-regulated status is being sought for the freeze tolerant *Eucalyptus* lines FTE 427 and FTE 435 (Federal Register, 2017); although we did not attempt to project yields for the genetically modified clones of *E. grandis* × *urophylla*, their productivity may be similar to *E. grandis* (Henri, 2001).

Yields of *E. grandis* on the east and west coasts of south Florida ranged from 45 m^3 ha^{-1} $year^{-1}$ to 85 m^3 ha^{-1} $year^{-1}$ (MAI, volume inside bark, 5-year rotation). Yields on interior sandy soils were lower, ranging from 35 m^3 ha^{-1} $year^{-1}$ to almost 45 m^3 ha^{-1} $year^{-1}$. Farther north, yields of *E. benthamii* were overall lower because of frost limitations. Nevertheless, highest yields were along the Atlantic and Gulf Coasts, ranging from 25 m^3 ha^{-1} $year^{-1}$ to 76 m^3 ha^{-1} $year^{-1}$, comparing favorably with potential yields (20 m^3 ha^{-1} $year^{-1}$ to 30 m^3 ha^{-1} $year^{-1}$) from *Pinus taeda* bioenergy plantings in the same coastal areas (Perdue et al., 2017). *Eucalyptus* biomass potential in the most productive coastal areas was 25 to 59.5 dry Mg ha^{-1} $year^{-1}$ for *E. grandis* and 19 to 42 dry Mg ha^{-1} $year^{-1}$ for *E. benthamii*.

Biomass yields from 3PG were used to model potential profitability by two criteria, land expectation value and internal rate of return. Generally we found that *E. grandis* had the highest potential profitability for bioenergy plantings in the south coastal areas of Florida where it had LEV of as much as \$1710 ha^{-1} and IRR values as high as 16.9% (excluding urban areas). Northern Florida, where frost occurs periodically, had the lowest LEVs and IRR percentages.

Wider deployment of *Eucalyptus* species beyond peninsular Florida in the southern USA is constrained by their susceptibility to freezing temperatures and has motivated a search for tolerant species. Two approaches are being pursued: (1) finding clones of frost tolerant *Eucalyptus* species and (2) genetically modifying clones of *E. grandis* × *urophylla* to be frost tolerant (Hinchee et al., 2009; Wear et al., 2015). In our modeling, weather limitations including frost reduced projected yields and profitability of *E. benthamii*, a putative frost-tolerant species.

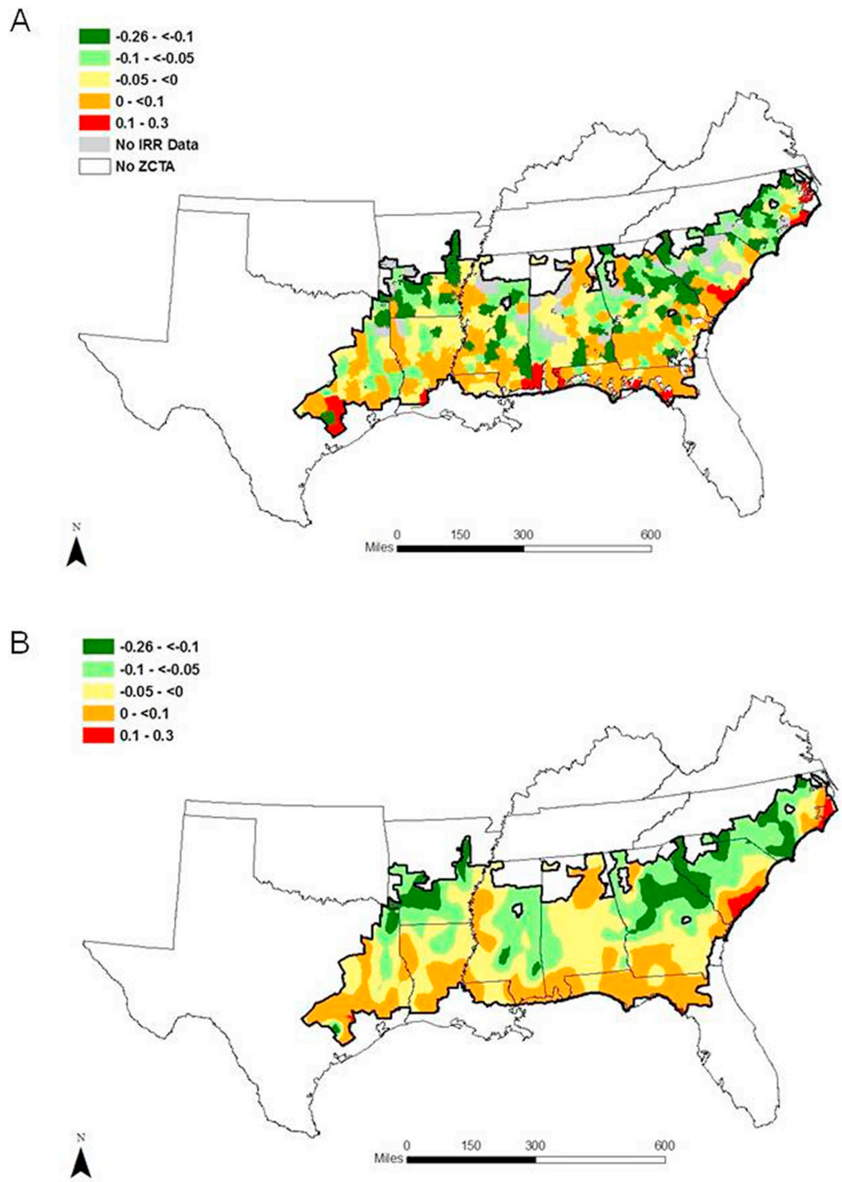

Fig. 8. Internal Rate of Return (IRR) of *Eucalypts benthamii* with a 5-year rotation length: (a) IRR at the 5-digit ZCTA level; (b) IRR smoothed by Simple Kriging.

Coastal areas produced the highest yields and profitability of *E. benthamii* but profitability (positive LEV) was limited to 12% of the sites theoretically within its operational range in the southern U.S. Our modeling suggests that *E. benthamii* has a limited operational range and is not suited for planting beyond Plant Hardiness Zone 8B. *E. grandis* is limited to frost-free areas of peninsular Florida where overall, it was more productive than *E. benthamii*; mean MAIs were 21.3 and 11.9 dry Mg ha^{-1} $year^{-1}$, respectively. A genetically modified freeze-tolerant *E. grandis* × *urophylla* that is as productive as *E. grandis* (Henri, 2001) likely would be similarly limited to hardiness zone 8B.

Beyond climatic adaptation, other limitations on wide-spread deployment of *Eucalyptus* include establishment costs, environmental issues, and public sentiment. High silvicultural costs for establishment and management may be a barrier to *Eucalyptus* production, particularly higher costs for planting material (Kellison et al., 2013) and certainty of productivity (Wear et al., 2015). Additionally, new weed control treatments are needed to control competing vegetation because herbicides used in pine plantations will damage *Eucalyptus* cuttings (Kellison et al., 2013; Minogue et al., 2018). The analysis of potential adoption of *Eucalyptus* in the South by Wear et al. (2015) focused on genetically modified clones but their results likely apply to all clones. They agreed that *Eucalyptus* was competitive with planted *Pinus*, particularly in the western Gulf Coast region, driven by increasing scarcity of broadleaved species. Although conversion of agricultural land was unlikely, there already was a trend to convert natural *Pinus* stands to plantations (Wear et al., 2013). Their analysis assumed uniform productivity across the southern USA, which they stated could be improved by location-specific productivity estimates (Wear et al., 2015).

Our results show where *Eucalyptus* is potentially profitable as a bioenergy crop in the southern USA indicating that a wholesale conversion of *Pinus* plantations is unlikely, a conclusion supported by (Wear et al., 2015). Climatic limitations and relatively costly inputs constrain profitable deployment of available *Eucalyptus* species to coastal areas of the southern US. Research underway to screen additional species and clones for freezing tolerance, including genetic modification, may yet result in widespread deployment of *Eucalyptus* spp. on pine sites. Modified silvicultural regimes may be less costly than the regime used in our analysis, increasing the competitiveness of *Eucalyptus* versus *Pinus*. However, if in the future operating costs, the stumpage price, and the interest rate vary from the assumption made in this paper, the profitability of *Eucalyptus* plantations will also change. As many studies indicated, higher operating costs and the interest rate will decrease the LEV and IRR (Yin et al. 1996, 1998; Langholtz et al., 2005, 2007). Alternatively, higher stumpage price will increase profitability. The sensitivity of profitability to these changes needs further assessment in the future.

Several aspects of our approach are open to further development and improvement; especially as more experimental results become available for performance of *E. benthamii* clones. We used a single silvicultural regime for all potential sites. This simplifying assumption was reasonable, given that our intent was to provide a coarse screening of potential profitability across the region. Relatedly, we used a single rotation length that may not have been the optimal rotation for all site conditions. Our economic analysis used the classical Faustmann formula that is best applied at the stand-level; alternatively, a forest-level approach (Yin et al., 1998) would explicitly incorporate land and capital costs. Such a forest-level approach would facilitate analyzing tradeoffs among different silvicultural regimes. We did not consider risk of disturbances in our analysis, although the coastal areas of highest LEV are also at greatest risk of hurricane impacts (Stanturf et al., 2007). Risk could be incorporated into the stand-level (e.g., Loisel, 2014) or forest-level approach (e.g., Yin and Newman, 1996).

Potential expansion of non-native *Eucalyptus* spp. has raised environmental concerns. Analysis to date suggests that use of *Eucalyptus* species as short-rotation woody crops poses manageable environmental risks (Goodrick and Stanturf, 2012; Callaham et al., 2013; Stanturf et al., 2013; Vose et al., 2015; Andreu et al., 2017; Maier et al., 2017). Nevertheless, if efforts to gain approval for unregulated release of freeze-tolerant *E. grandis* × *urophylla* (awaiting final decision at the time of this writing; cf., Federal Register, 2017) are successful, conflation of issues (an exotic species with genetic modification of some clones) may give rise to significant public opposition. Further study of potential environmental effects could use our spatially explicit results to focus analysis and inform potential debate.

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References

Almeida, A.C., Landsberg, J.J., Sands, P.J., 2004. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. Forest Ecol Manag 193, 179–195.

Almeida, A.C., Siggins, A., Batista, T.R., Beadle, C., Fonseca, S., Loos, R., 2010. Mapping the effect of spatial and temporal variation in climate and soils on Eucalyptus plantation production with 3-PG, a process-based growth model. Forest Ecol Manag 259, 1730–1740.

Andreu, A., Ottmar, R.D., Prichard, S.J., 2017. Evaluation of Potential Fire Behavior in Genetically Engineered Freeze-Tolerant (FTE) Plantations of the Southern United States. In: USDA-APHIS, September 2013, ArborGen, Inc. Petition (11–019-01p) for Determination of Non-regulated Status for Freeze Tolerant Eucalyptus Lines FTE 427 and FTE 435 Draft Environmental Impact Statement, April, 2017, Appendix D: USDA-Forest Service Report on the Potential Fire Risk of Freeze-Tolerant Eucalyptus. Washington, DC.

Butnor, J., Johnsen, K., Anderson, P., Hall, K., Halman, J., Hawley, G., Maier, C., Schaberg, P.G., 2018. Growth, photosynthesis, and cold tolerance of *Eucalyptus benthamii* planted in the piedmont of North Carolina. For. Sci. 23, 748.

Callaham, M.A., Stanturf, J.A., Hammond, W.J., Rockwood, D.L., Wenk, E.S., O'Brien, J.J., 2013. Survey to evaluate escape of *Eucalyptus* spp. seedlings from plantations in Southeastern USA. Int J Forest Res. https://doi.org/10.1155/2013/946374. Article ID 946374, 10 pages, 2013.

Chang, S.J., 1998. A generalized Faustmann model for the determination of optimal harvest age. Can. J. For. Res. 28, 652–659.

Daystar, J., Reeb, C., Gonzalez, R., Venditti, R., Kelley, S.S., 2015. Environmental life cycle impacts of cellulosic ethanol in the Southern US produced from loblolly pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass using a thermochemical conversion pathway. Fuel Proc Technol 138, 164–174.

Dickens, E., Borders, B., Jackson, B., 2011. Short rotation woody crops yield estimates for Georgia growers. In: Series Paper 1. University of Georgia Warnell School of Forestry and Natural Resources, Athens, GA.

Dougherty, D., Wright, J., 2012. Silviculture and economic evaluation of eucalypt plantations in the Southern US. Bioresources 7, 1994–2001.

Dye, P., Jacobs, S., Drew, D., 2004. Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. Forest Ecol Manag 193, 197–218.

El Kasmioui, O., Ceulemans, R., 2012. Financial analysis of the cultivation of poplar and willow for bioenergy. Biomass Bioenergy 43, 52–64.

Federal Register, 2017. Vol. 82, No. 76/Friday, April 21, 2017/Notices 18759. Identification of freeze tolerant *Eucalyptus* species and hybrids extends the potential commercial range for *Eucalyptus* well beyond Current plantings in southern. USDA APHIS DEIS concluded that the Preferred Alternative, FTE 427, FTE 435, and their progeny would no longer be subject to APHIS Biotechnology regulations (7 CFR part 340) as they would have been determined unlikely to pose plant pest risk.

Ghezehei, S.B., Shifflett, S.D., Hazel, D.W., Nichols, E.G., 2015. SRWC bioenergy productivity and economic feasibility on marginal lands. J. Environ. Manag. 160, 57–66.

Gonzalez, R., Treasure, T., Wright, J., Saloni, D., Phillips, R., Abt, R., Jameel, H., 2011. Exploring the potential of *Eucalyptus* for energy production in the Southern United States: Financial analysis of delivered biomass. Part I. Biomass Bioenergy 35, 755–766.

Goodrick, S.L., Stanturf, J.A., 2012. Evaluating potential changes in fire risk from *Eucalyptus* plantings in the Southern United States. Int J Forest Res 2012https://doi.org/10.1155/2012/680246. Article ID 680246, 9 pages, 2012.

Gordon, D.R., Flory, S.L., Cooper, A.L., Morris, S.K., 2012. Assessing the invasion risk of *Eucalyptus* in the United States using the Australian weed risk assessment. Int J Forest Res 2012https://doi.org/10.1155/2012/203768. Article ID 203768, 7 pages, 2012.

Henri, C.J., 2001. Soil-site productivity of *Gmelina arborea, Eucalyptus urophylla* and *Eucalyptus grandis* forest plantations in western Venezuela. Forest Ecol Manag 144, 255–264.

Hinchee, M., Rottmann, W., Mullinax, L., Zhang, C., Chang, S., Cunningham, M., Pearson, L., Nehra, N., 2009. Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cell Dev-Pl 45, 619–629.

Immerzeel, D.J., Verweij, P., Hilst, F., Faaij, A.P., 2014. Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy 6, 183–209.

Junior, H.d.J.E., Nakashima, G.T., Yamaji, F.M., Guerra, S.P.S., Ballarin, A.W., 2017. *Eucalyptus* short-rotation coppice for solid fuel production. Ind. Crop. Prod. 108, 636–640.

Kellison, R., Lea, R., Marsh, P., 2013. Introduction of *Eucalyptus* spp. into the United States with special emphasis on the Southern United States. Int J Forest Res 2013https://doi.org/10.1155/2013/189393. Article ID 189393, 9 pages, 2013.

Landsberg, J., Waring, R., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecol Manag 95, 209–228.

Landsberg, J., Waring, R., Coops, N., 2003. Performance of the forest productivity model 3-PG applied to a wide range of forest types. Forest Ecol Manag 172, 199–214.

Langholtz, M., Carter, D.R., Rockwood, D.L., Alavalapati, J.R., Green, A., 2005. Effect of dendroremediation incentives on the profitability of short-rotation woody cropping of *Eucalyptus grandis*. Forest Policy Econ. 7, 806–817.

Langholtz, M., Carter, D.R., Rockwood, D.L., Alavalapati, J.R., 2007. The economic feasibility of reclaiming phosphate mined lands with short-rotation woody crops in Florida. J Forest Econ 12, 237–249.

Loisel, P., 2014. Impact of storm risk on Faustmann rotation. Forest Policy Econ. 38, 191–198.

Maier, C.A., Albaugh, T.J., Cook, R.I., Hall, K., McInnis, D., Johnsen, K.H., Johnson, J., Rubilar, R.A., Vose, J.M., 2017. Comparative water use in short-rotation *Eucalyptus benthamii* and *Pinus taeda* trees in the Southern United States. Forest Ecol Manag 397, 126–138.

Marland, G., 2010. Accounting for carbon dioxide emissions from bioenergy systems. J. Ind. Ecol. 14, 866–869.

McKenney, D.W., Weersink, A., Allen, D., Yemshanov, D., Boyland, M., 2014. Enhancing the adoption of short rotation woody crops for bioenergy production. Biomass Bioenergy 64, 363–366.

Medema, E.L., Lyon, G.W., 1985. The determination of financial rotation ages for coppicing tree species. For. Sci. 31, 398–404.

Meskimen, G., Francis, J., 1990. *Eucalyptus grandis* Hill ex Maiden. Rose gum eucalyptus. In: Burns, R.M., Honkala, B.H. (Eds.), Silvics of North America Vol. 2, Hardwoods. US

Department of Agriculture, Forest Service, Agriculture Handbook 654. pp. 305–312.
Minogue, P.J., Osiecka, A., Lauer, D.K., 2018. Selective herbicides for establishment of *Eucalyptus benthamii* plantations. New For. 49, 529–550.
Oliver, M.A., Webster, R., 1990. Kriging: a method of interpolation for geographical information systems. Int. J. Geogr. Inf. Syst. 4, 313–332.
Perdue, J.H., Stanturf, J.A., Young, T.M., Huang, X., Dougherty, D., Pigott, M., Guo, Z., 2017. Profitability potential for *Pinus taeda* L.(loblolly pine) short-rotation bioenergy plantings in the southern USA. Forest Policy Econ. 83, 146–155.
Perlack, R.D., Eaton, L.M., Turhollow Jr., A.F., Langholtz, M.H., Brandt, C.C., Downing, M.E., Graham, R.L., Wright, L.L., Kavkewitz, J.M., Shamey, A.M., 2011. US billion-ton update: biomass supply for a bioenergy and bioproducts industry. US Department of Energy Oak Ridge National Laboratory, Oak Ridge, TN.
Pirraglia, A., Gonzales, R., Saloni, D., Wright, J., Denig, J., 2011. Fuel properties and suitability of *Eucalyptus benthamii* and *Eucalyptus macarthurii* for torrefied wood and pellets. Bioresources 7, 0217–0235.
Robledo-Abad, C., Althaus, H.J., Berndes, G., Bolwig, S., Corbera, E., Creutzig, F., Garcia-Ulloa, J., Geddes, A., Gregg, J.S., Haberl, H., 2017. Bioenergy production and sustainable development: science base for policymaking remains limited. GCB Bioenergy 9, 541–556.
Rockwood, D.L., 2012. History and status of *Eucalyptus* improvement in Florida. Int J Forestry Res 2012https://doi.org/10.1155/2012/607879. Article ID 607879, 10 pages, 2012.
Rockwood, D., Rudie, A., Ralph, S., Zhu, J., Winandy, J., 2008. Energy product options for *Eucalyptus* species grown as short rotation woody crops. Int. J. Mol. Sci. 9, 1361.
Sands, P., Landsberg, J., 2002. Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. Forest Ecol Manag 163, 273–292.
Stanturf, J.A., Kellison, R.C., Broerman, F., Jones, S.B., 2003. Productivity of southern pine plantations: where are we and how did we get here? J Forest 101, 26–31.
Stanturf, J.A., Goodrick, S.L., Outcalt, K.W., 2007. Disturbance and coastal forests: a strategic approach to forest management in hurricane impact zones. Forest Ecol Manag 250, 119–135.
Stanturf, J.A., Vance, E.D., Fox, T.R., Kirst, M., 2013. Eucalyptus beyond its native range: Environmental issues in exotic bioenergy plantations. Int J Forest Res 2013https://doi.org/10.1155/2013/463030. Article ID 463030, 5 pages, 2013.
Stape, J.L., Ryan, M.G., Binkley, D., 2004. Testing the utility of the 3-PG model for growth of *Eucalyptus grandis* × *urophylla* with natural and manipulated supplies of water and nutrients. Forest Ecol Manag 193, 219–234.
Stape, J.L., Fox, T., Albaugh, T., Alvarez, J., Rubilar, R., 2011. Cold-tolerance and initial growth of 38 *Eucalyptus* species in the Southeastern United States. In: Proceedings IUFRO Working Group 2.08.03, Improvement and Culture of *Eucalyptus*. Porto Seguro, Bahia, pp. 311–312.
Tarr, N.M., Rubino, M.J., Costanza, J.K., McKerrow, A.J., Collazo, J.A., Abt, R.C., 2017. Projected gains and losses of wildlife habitat from bioenergy-induced landscape change. GCB Bioenergy 9, 909–923.
Vance, E.D., Loehle, C., Wigley, T.B., Weatherford, P., 2014. Scientific basis for sustainable management of *Eucalyptus* and *Populus* as short-rotation woody crops in the US. Forests 5, 901–918.
Vanhala, P., Repo, A., Liski, J., 2013. Forest bioenergy at the cost of carbon sequestration? Curr. Opin. Environ. Sustain. 5, 41–46.
Vose, J.M., Miniat, C.F., Sun, G., Caldwell, P.V., 2015. Potential implications for expansion of freeze-tolerant *Eucalyptus* plantations on water resources in the southern United States. For. Sci. 61, 509–521.
Wear, D.N., Huggett, R., Li, R., Perryman, B., Liu, S., 2013. Forecasts of forest conditions in regions of the United States under future scenarios: a technical document supporting the Forest Service. In: 2012 RPA Assessment. General Technical Report-Southern Research Station. USDA Forest Service.
Wear, D.N., Dixon, E., Abt, R.C., Singh, N., 2015. Projecting potential adoption of genetically engineered freeze-tolerant *Eucalyptus* in the United States. For. Sci. 61, 466–480.
Williams, P.R., Inman, D., Aden, A., Heath, G.A., 2009. Environmental and sustainability factors associated with next-generation biofuels in the US: what do we really know? Environ Sci Technol 43, 4763–4775.
Wright, J., 2010. Short-rotation woody crops for bioenergy and biofuels. In: Wood-Based Biofuels, Biomass, and Bioenergy: Opportunities and Challenges. Rouge, LA, Baton.
Wright, L., Eaton, L., Perlack, R., 2010. Published and reported woody crop biomass yield data. In: Paper presented October 19, 2010 at the Short Rotation Woody Crops Working Group Meeting, Oak Ridge, TN.
Yin, R., Newman, D.H., 1996. The effects of catastrophic risk on forest investment. J. Environ. Econ. Manag. 36, 186–197.
Yin, R., Pienaar, L.V., Aronow, M.E., 1998. The productivity and profitability of fiber farming. J Forest 96 (11), 13–18.
Zalesny, R.J., Cunningham, M., Hall, R., Mirck, J., Rockwood, D., Stanturf, J., Volk, T., 2011. Woody biomass from short rotation energy crops. In: Zhu, J.J.Y., Zhang, X., Pan, X.J. (Eds.), Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass. American Chemical Society, Washington, DC, pp. 27–63.