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A spatially explicit model to identify suitable sites to establish dedicated woody energy crops

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ABSTRACT

Biomass has gained considerable attention in the southern United States (US) mainly because of its potential to partially replace fossil fuels and develop a sustainable bioenergy industry. Dedicated energy crops could offer a reliable and sustainable biomass supply, but there is limited research identifying suitable sites and evaluating their economic feasibility. This study developed a model to identify potential sites to establish dedicated energy crops based on the economic feasibility of short rotation woody crops. Site suitability was based on site-specific woody biomass yield, production costs, and delivered biomass prices. Transportation costs including off-road and on-road transportation costs were based on travel time from each potential plantation site to the nearest conversion facility. Break-even biomass amounts were obtained by considering production costs and biomass price, and potential biomass yield was estimated based on site index. Break-even biomass amounts were then compared with potential biomass yields to determine suitable sites to establish dedicated energy crops. To illustrate the applicability of the model, it was applied to a four-county test area in northern Kentucky with a diverse land cover and ownership, relatively extensive transportation network, and presence of existing conversion facilities, conditions which are common in the Ohio River Valley region and much of the southern US.

1. Introduction

Bioenergy has received considerable attention because the potential it offers as a renewable energy source. In the southern US, there is a developing interest in bioenergy as the region offers excellent growing conditions for producing short rotation woody crops with the potential to partially replace fossil fuels and supply feedstock for a sustainable bioenergy industry [1]. Dedicated woody energy crops offer economic advantages compared with natural forests because of their ability to provide a stable supply of feedstock and relatively lower collection and handling costs [1]. When located on fertile soils and intensively managed, these crops can experience fast growth rates and produce high biomass yields with

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rotation as low as five years [2]. Furthermore, establishing dedicated energy crops can provide numerous environmental benefits (i.e., improve soil quality, reduce soil and water erosion, increase carbon sequestration, reduce greenhouse gas emissions, and improve wildlife habitat and biodiversity) as well as promote rural development, and create job opportunities.

The bioenergy industry relies on the quality and quantity of available biomass feedstock and the ability to efficiently collect, handle, and transport it to conversion facilities [3]. Several studies have focused on finding the best location of conversion facilities, which is essential for economically feasible bioenergy production due to scattered nature of the feedstock and the relatively high associated transportation costs. These studies have used mixed-integer programming to find the facility location that minimizes production cost of the entire biomass supply chain including biomass availability, plant investment and capacity, transportation costs, biomass price, project financing and taxes [4–6]. Other studies have also used geographic information systems (GIS) and spatial analysis to directly address the spatial nature of the facility location problem [7–9]. Although solving the facility location problem is important, the relatively large initial investments hinder the establishment of new facilities making it very likely that biomass will be used for energy production at existing conversion facilities. Identifying suitable sites for dedicated energy crops to supply existing facilities then becomes crucial to establish an economically feasible and environmentally sustainable bioenergy production industry.

Biomass yield from energy crops is dependent on species, site conditions, soil productivity, and management intensity [10], and for a given site, the economic feasibility of dedicated energy crops is greatly influenced by the associated transportation cost to conversion facilities. Moreover, biomass prices are dynamic due to changes in production practices, market conditions, and government incentives. A few studies have focused on identifying suitable sites for these crops. For example, Ranney and Cushman [11] linked a woody crop productivity model with land availability to produce potential biomass yields from short rotation woody crops for each county in the southern US. However, this large-scale study did not account for transportation costs to existing facilities. Graham [12] developed a GIS-based model to identify suitable sites for switchgrass (*Panicum virgatum*) as an energy crop feedstock in eleven southern US states based on production costs as well as on negative environmental implications such as soil erosion and loss of nitrogen. However, this study focused on a single perennial native grass species and did not include woody biomass species. Goerndt et al. [13] estimated availability of woody biomass from native forest in 20 states in the northern region of the US, but dedicated energy crops were not included in their analysis because of the lack of markets. Other studies developed a spatial model to estimate biomass production costs and combined them with expected biomass yield of *Eucalyptus saligna* in Kauai Island Hawaii to estimate biomass delivery costs [14–16]. Although these aforementioned studies are helpful to understand the relevance of selecting appropriate sites for bioenergy crops, automated approaches able to address site-specific soil productivity and production costs applicable to the conditions and species in the eastern US have not been developed. Further, previous studies have only dealt with a single conversion facility and there is limited understanding of how multiple facilities might affect the spatial distribution of site availability.

To address the limitations of existing studies and the dynamic and spatial nature of biomass production, we developed an automated model to identify suitable sites for dedicated energy crops based on biomass prices, expected biomass yields as well as establishment, management, harvesting, and transportation costs. Our model considers both on-road and off-road transportation costs to take into account the location of potential sites relative to existing roads and to the nearest conversion facility. We identified sites where biomass production for short rotation woody crops is economically feasible by comparing break-even biomass amounts with expected biomass yields. Although the biomass yield estimates used in this study are species dependent, they are based on site index which can be obtained from soil data readily available for the entire US increasing the applicability of our model. Using spatial analysis tools available in GIS software, the model can be applied to identify suitable sites for dedicated energy crops for large landscapes and understand how different economic factors can influence the amount of land available and its spatial distribution across the landscape. The model was applied to four counties in northern Kentucky (Boone, Gallatin, Carroll, and Trimble) that present conditions commonly found in the entire Ohio River Valley and much of the southeastern US including a diverse land use, mostly privately owned small land parcels, and the presence of power plants with the ability to co-fire biomass with coal. While this study was conducted in northern Kentucky, the developed model can be applied to other geographic locations, and can inform managers and landowners interested in utilizing biomass for energy production.

2. Methodology

The model identified sites to establish dedicated energy crops that result in a positive economic return by comparing site specific break-even biomass amounts with expected biomass yields. The model first estimated production costs (establishment, management, harvesting and on-road and off-road transportation) and combined them with biomass prices to determine the break-even biomass amount. Potential biomass yield was estimated based on soil productivity and management scenarios. Land parcels where the expected biomass yield exceeded the break-even biomass amount were considered suitable for establishing dedicated energy crops.

The model was designed with generality so it can be applied in any geographic region and at any spatial scale, given availability of data. However, below we provide a description of a four-county area in northern Kentucky used as an example to show the model application and to provide context for the input data used in the main components of the model: *i*) biomass price and production costs, *ii*) break-even biomass amount calculations, and *iii*) biomass yield estimation.

2.1. Test area and input data

Four counties in northern Kentucky: Trimble, Carroll, Gallatin and Boone were selected as the test area. This area is about 169,566 ha in size and is comprised of land cover types including evergreen forest, deciduous forests, pasture/hay, other agricultural crops, and developed area (Fig. 1). Land cover data in a 30-m raster resolution was obtained from the USDA National Agricultural Statistics Services [17]. The land cover raster was reclassified into a 90-m resolution to decrease the total number of grid cells covering the test area and reduce computing time, and create grid cells large enough to represent land parcels of manageable size. A transportation road layer covering the test area was obtained from the Kentucky Geography Network [18]. For any local roads where speed limits were unavailable, speed limits of 16 km h^{-1}, 40 km h^{-1}, and 56 km h^{-1} were assigned for dirt roads, city roads, and county roads, respectively. There are three conversion facilities in the test area with the ability to co-fire biomass with coal for power generation located in Bedford, Ghent, and Rabbit Hash, KY, and owned by Louisville Gas and Electric, Kentucky Utilities, and Duke Energy, respectively.

We selected sweetgum (*Liquidambar styraciflua* L.) as a potential species to establish short rotation woody crops across the test area because it is one of the most adaptable hardwood species with an ability to grow on a wide range of soil and site qualities. The management and silvicultural operations for establishing and growing sweetgum are well understood and genetic improvements in sweetgum have been successful [19]. Further, sweetgum coppices well, it is generally insect and disease resistant, and it has been recommended as a potential species for biomass production in the southeastern states including Kentucky [20,21].

2.2. Biomass prices and production costs

Biomass prices are influenced by market conditions and biomass availability, among other factors. In this analysis, we considered a delivered biomass price of 40 \$ t^{-1} (dry basis) at the three facilities based on price ranges reported by Kline and Coleman [20]. Although delivered prices might be region-specific, similar prices have also been used in other recent studies [22,23].

Establishment and management costs vary widely for different species. Considering a rotation age of 12 years, Kline and Coleman [20] reported costs ranging from 778 to 1743 \$ ha^{-1} for sweetgum. These costs are based on treatments including site preparation, planting, and herbicide, pesticide and fertilizer applications incurred at different years throughout the rotation. We used the mid-cost range value of establishment and management treatments from Kline and Coleman [20], resulting in 1260 \$ ha^{-1} (Table 1).

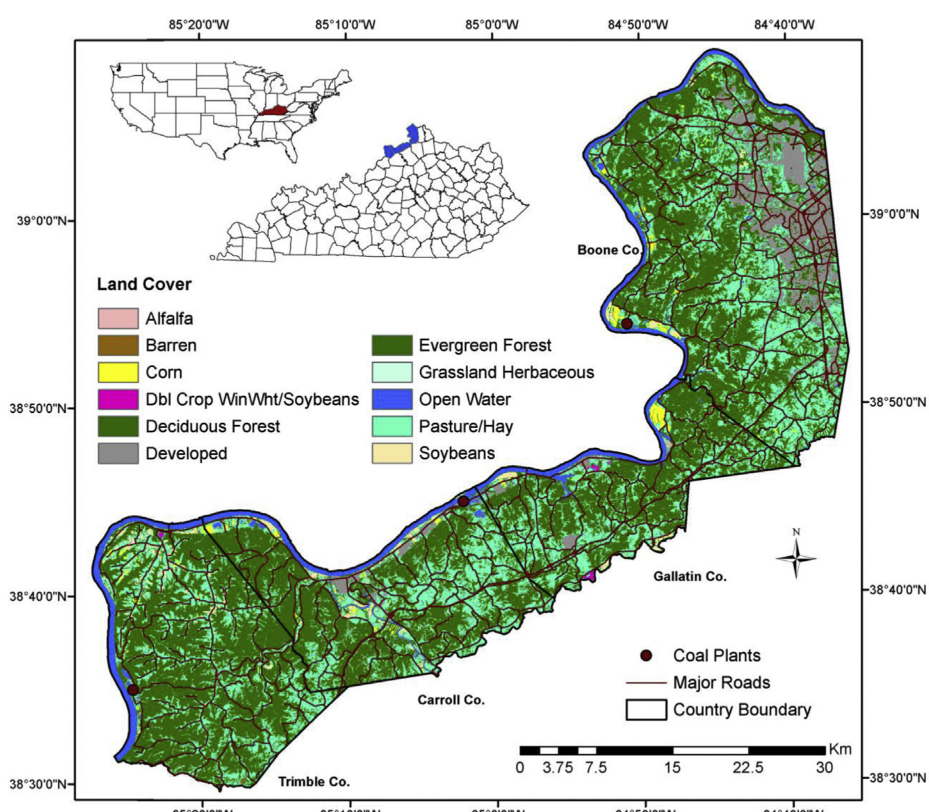

Fig. 1 – Land cover across the four northern Kentucky counties considered in this study.

Table 1 – Estimated establishment and management costs for a 12-year rotation of sweetgum energy crops (Kline and Coleman [20]).

Year	Treatment	Cost ($ ha^{-1})
1	Site preparation	370.5
	Planting stock	216
	Planting	111.5
	Herbicide	278
	Pesticide	
2	Herbicide	129.5
	Pesticide	
3	Pesticide	
4	Pesticide	
	Fertilize	31
6	Fertilize	31
8	Fertilize	31
10	Fertilize	31
12	Fertilize	31
Total cost		1260.5

Proximity to conversion facilities can have a large influence on the economic feasibility of dedicated energy crops because transportation cost is the largest cost component in bioenergy production. In our model, transportation cost included the cost of moving biomass from each grid cell to an existing road, referred as off-road transportation cost, and the cost of transporting biomass along existing roads to the nearest facility, on-road transportation cost. Off-road transportation cost was calculated based on harvesting equipment and the associated travel time from a given grid cell to the nearest existing road. New Holland (NH) forage harvesters have been used to harvest willow and poplar dedicated energy crops in the eastern US [24,25] and have been recommended in Kentucky [21]. We assumed biomass harvesting is done by a mechanized system comprised of a forage harvester (such as the NH forage harvester or a similar machine) that cuts, chips, and blows chips into a trailer pulled by a tractor, which transports the chips to road side. Off-road transportation cost referred to the cost of transporting chips by the tractor from stump to road side, and for a given grid cell was calculated by multiplying the Euclidean distance (km) by the fraction between the tractor rental rate ($ h^{-1}) and the average tractor operating speed (km h^{-1}). The Euclidean distance from the center of a grid cell to the closest point along an existing road was determined using the Euclidean Distance function in the Spatial Analyst ArcToolbox in ArcMap 10. We considered a tractor rental rate of 60 $ h^{-1} and an average speed of 6.5 km h^{-1} based on data from an economic analysis tool developed for willow short-rotation crops for chip production [26]. The economic analysis tool for willow estimated a biomass harvesting cost for this mechanized system of approximately 15 $ t^{-1} (dry basis), which included off-road transportation by the tractor and considered a forage harvester rental rate of 180 $ h^{-1}. In our model, biomass harvesting cost was divided into the actual cost of the cutting, chipping, and blowing chips in to the trailer (CCB cost) performed by the forage harvester, and the off-road transportation cost to account for the location of grid cells with respect to existing roads, which can significantly affect biomass harvesting cost. The CCB cost was assumed constant for all grid cells because it is not affected by the proximity to road side and was calculated by prorating the total harvesting cost of 15 $ t^{-1} (dry basis) by the rental rate contribution of the forage harvester (180 $ h^{-1}) to the combined mechanize system (180 $ h^{-1} + 60 $ h^{-1}). This resulted in a constant CCB cost of 11.25 $ t^{-1} (dry basis) across the test area.

For a given grid cell, its closest point along an existing road was identified using the Euclidean Allocation function in the Spatial Analyst ArcToolbox. On-road transportation cost was then calculated based on a chipvan's (commonly used to transport biomass) operating cost and the travel time along the least-cost route from the existing road to the nearest facility. Operating cost for a 25 t chipvan was calculated using a machine rate calculation spreadsheet presented by Brinker et al. [27], which takes into account fixed or ownership costs, variable or operating costs, and labor and fuel costs. The resulting machine rate was 78.22 $ h^{-1}. The road transportation network was partitioned into 90-m road sections to maintain consistency with the land cover grid cell resolution and more accurately represent where off-road biomass transportation routes would converge with existing roads. Travel time was then calculated using speed limits for each road section in the road transportation layer. For a given grid cell, we used the New Origin-Destination (OD) Cost Matrix function in the Network Analyst ArcToolbox to determine the shortest travel time from its closest point along an existing road to the closest facility. On-road transportation cost for the grid cell was then calculated by multiplying the shortest travel time (h) by the chipvan operating cost ($ h^{-1}). Off-road and on-road transportation costs were calculated for each of the 209,341 90-m grid cells covering the 169,566 ha test area.

2.3. Break-even biomass amount calculation

Biomass price and production costs by grid cell were combined to determine the break-even biomass amount that produces a land expectation value (LEV) of zero. LEV was calculated using the Faustmann's formula [28]:

$$\mathrm{LEV} = \frac{[P \bullet V - C] \bullet e^{-rt}}{1 - e^{-rt}} \tag{1}$$

where P is the delivered price of biomass ($ t^{-1}, dry basis), V is the biomass amount (t), C is the total production cost ($), r is the discount rate, and t is the rotation age. Although LEV calculations are commonly based on stumpage prices, we used delivered biomass price instead to obtain the break-even biomass amount. We assumed coppice regeneration for sweetgum for an infinite rotation (mainly because of the uncertainty about the number of coppice rotations that could occur before replanting would be necessary) and our LEV equation was adjusted to account for a one time establishment cost that occurs only on the first year of the initial rotation. A discount rate of 5% was considered for analysis. After combining all production costs, the resulting LEV equation is presented below:

$$\mathrm{LEV} = \frac{\left[P \bullet V(t) - \left(\mathrm{CCB} + \frac{C_{\mathrm{off}}}{L_{\mathrm{trailor}}} + \frac{C_{\mathrm{on}}}{L_{\mathrm{van}}}\right) \bullet V(t)\right] \bullet e^{-rt} - C_{\mathrm{HPF}} \bullet A}{1 - e^{-rt}} - C_{\mathrm{SP}} \bullet A \tag{2}$$

Table 2 – Categorization of soil sub-factors into poor, medium, and best quality and associated score values (indicated in brackets) used to calculate site index.

Major soil factor	Soil sub factor	Poor	Medium	Best
Physical condition	Soil depth	<0.61 m [−2]	0.61–1.22 m [4]	>1.22 m [6]
	Texture	Fine, clayey [1]	Coarse, sandy [2]	Medium, silty or loamy [4]
	Compaction	Bulk density >1.7 t m^{-3} [−2]	Bulk density 1.4–1.7 t m^{-3} [4]	Bulk density <1.4 t m^{-3} [6]
	Structure	Massive [0]	Prismatic [4]	Granular, structureless [6]
	Land use	Intensive cultivation [2]	Open with grass cover [5]	Forest cover [8]
Moisture availability during growing season	Water table depth	<0.3 m [unsuitable]; >3.05 m [−3]	0.30–0.61 m; 1.81–3.05 m [3]	0.61–1.81 m [6]
	Presence of pans	Inherent pan [−3]	Plowpans [3]	No pans [6]
	Topographic position	Upland [−2]	Stream terraces [3]	Floodplain [5]
	Microsite	Convex; ridge [−2]	Level; flat [1]	Concave; depression [2]
	Structure	Structureless [−1]	Prismatic [3]	Granular; structureless [5]
	Texture	Sandy [0]	Clayey [2]	Silty or loamy [5]
	Flooding	None [0]	Winter only [3]	Winter through spring [5]
	Land use	Intensive cultivation [0]	Open with grass cover [1]	Forest cover [2]
Availability nutrient	Geological source	Coastal Plain [2]	Mixed Coastal Plain and other [4]	Mississippi River, Loess, Blackland [5]
	Land use	Intensive cultivation [1]	Open with grass cover [3]	Forest cover [5]
	Organic matter	<1% [−2]	1–2% [2]	>2% [4]
	Topsoil depth	<7.62 cm [−3]	7.62–15.24 cm [2]	>15.24 cm [5]
	Soil age	Old [0]	Medium [2]	Young [4]
	pH	<4.5 or >8.5 [−1]	4.5–5.5 or 7.6–8.5 [0]	5.5–7.5 [1]
Aeration	Structure	Massive [−2]	Prismatic [4]	Granular; structureless [8]
	Swampiness	Waterlogged all year [unsuitable]	Wet January–July [4]	Wet in winter only [8]
	Mottling	Mottled to surface or gray mineral soil [−2]	None to 20.32 cm depth [5]	None to 45.72 cm depth [7]
	Soil color	Gray [−2]	Yellow, brownish-gray [4]	Black, brown, red [7]

Therefore, the resulting formula used to determine the break-even biomass amount is presented in Eq. (3).

$$V = \frac{A}{t} \cdot \frac{C_{HPF} + C_{SP} \cdot (1 - e^{-rt})}{\left[P - \left(\frac{C_{off}}{L_{trailer}} + \frac{C_{on}}{L_{van}} + CCB\right)\right] \cdot e^{-rt}} \quad (3)$$

where, C_{HPF} is the sum of discounted costs for herbicide, pesticide and fertilizer treatments ($ ha^{-1}) incurred during the rotation, C_{SP} is the site preparation and plantation cost occurring on the first year, A is the grid cell size (ha), C_{off} is the off-road transportation cost ($), C_{on} is the on-road transportation cost ($), CCB is the cost of the cutting, chipping, and blowing chips into the trailer, $L_{trailer}$ and L_{van} are the loading capacity (t) of the trailer and the chipvan.

2.4. *Biomass yield estimation*

Forecasting biomass yields based on site-specific conditions are non-trivial as detailed information about soil properties, weather conditions, species, genetic improvement, and management scenario is required. For simplicity and for the purpose of illustrating the applicability of our approach, we estimated biomass yield following the study of Kline and Coleman [20] that assigns an average biomass yield for low, medium, and high quality sites, which we determined based on site index estimates.

Site index was calculated based on a weighted score of four major soil factors: physical condition, moisture availability during the growing season, nutrient availability, and aeration [29]. These major soil factors are comprised of a number of sub-factors (soil–site properties), each one contributing differently to the associated major soil factor weight. We used the same weights as those presented by Baker and Broadfoot [29] for major soil factors and sub-factors. Each sub-factor was classified into poor, medium, and best quality and assigned a score. Table 2 shows the range of soil conditions used to classify sub-factors and the associated scores used to obtain site index. Score values are based on the contribution of each sub-factor to the growth of the particular species [29]. Soil–site properties across the test area by each grid cell were obtained from spatial and tabular soil data from the Soil Survey Geographic Database (SSURGO) and matched as closely as possible to the range of conditions provided by Baker and Broadfoot [29] to assign appropriate scores. Site index was then calculated by adding all scores assigned to a given grid cell. As recommended by Baker and Broadfoot [29], site index values between 22.9 and 38.1 m were considered acceptable for establishing sweetgum, and grid cells with site index values below this range were considered unsuitable.

Biomass yield was obtained from Kline and Coleman's [20] study that reported low, average, and high potential biomass yield estimates based on interviews with practitioners from forest products companies with over 50 years of experience growing bioenergy crops. These estimates are based on fixed management scenarios (see Table 1), thus rather than using the exact estimate values, we scaled the potential biomass yield in each grid cell to allow for variability due to changes in site micro-conditions. The biomass yield estimate for a given grid cell was obtained by scaling its site index value to the site index values suitable for establishing bioenergy crops (22.9–38.1 m) and then relating it to the range of estimates from Kline and Coleman [20], 4 to 8 t^{-1} ha^{-1} yr^{-1} (dry basis).

To identify suitable and economically efficient sites to establish short-rotation sweetgum plantations, the scaled biomass yield estimated by grid cell was compared with the break-even biomass amount calculated from the LEV equation [Eq. (3)]. Grid cells with break-even biomass amounts lower than the scaled biomass yields obtained from the site index calculation were considered suitable and economically efficient for sweetgum bioenergy crops.

3. Results

3.1. *Production costs*

In our analysis, production costs are comprised of two sets of costs; a location independent set including establishment and management as well as CCB costs, which are the same for all

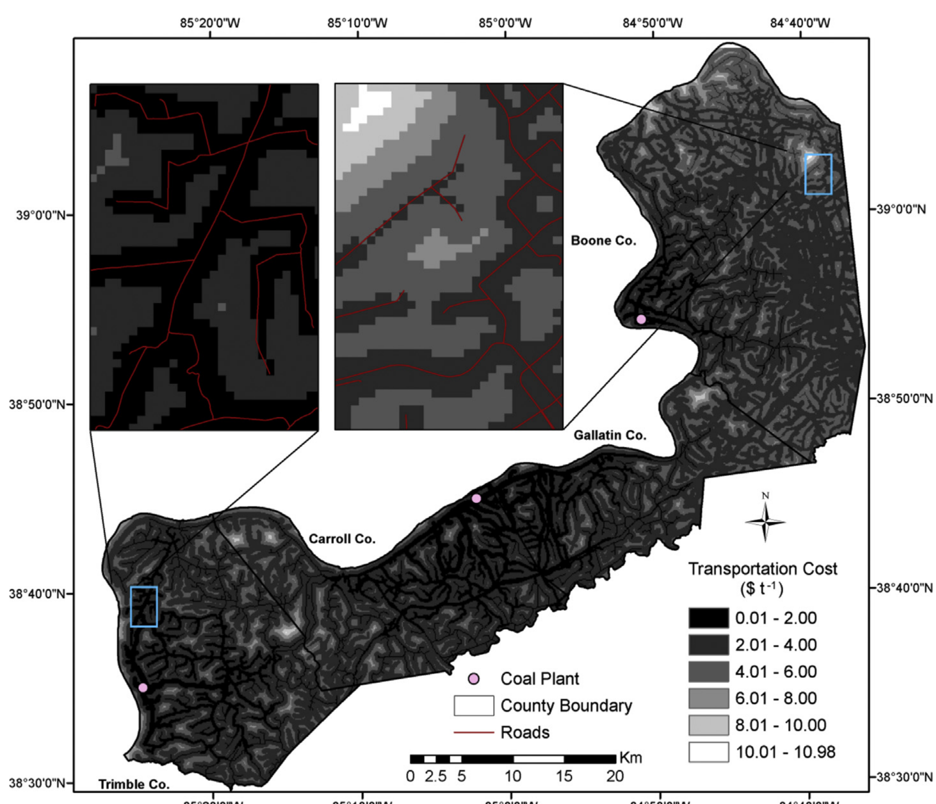

Fig. 2 – Spatial pattern of total transportation cost by grid cell across the test area.

grid cells across the test area, and a location dependent set including off-road and on-road transportation costs, which vary based on the distance from any given grid cell to existing roads and to conversion facilities.

As aforementioned, off-road transportation costs were calculated based on the tractor travel time along the Euclidean distance from a given grid cell to the nearest road, tractor rental rate, and average speed. Off-road distance across the test area varied between 0 and 1.27 km with an average of 210 m. Considering a speed limit of 6.5 km h^{-1}, round trip off-road travel time from grid cell to existing roads varied from 0 to 24 min, with an average of 4.0 min. Using the 60 \$ h^{-1} rental rate, the resulting off-road transportation cost ranged from 0 \$ for grid cells next to existing roads to 23.5 \$ for grid cells farthest away from roads, with an average of 3.8 \$. Lastly, considering a trailer loading capacity of 6 t, off-road transportation costs ranged from 0 to 3.91 \$ t^{-1}, with an average cost of 0.63 \$ t^{-1}.

Similarly, on-road transportation costs were calculated based on the chipvan travel time along the least-time route from existing roads to the nearest conversion facility, and the chipvan operating cost of 78.22 \$ h^{-1}. On-road distance across the test area varied between 0.23 m and 46 km, with an average of 22 km. One-way travel time ranged from 0.1 min for grid cells near the facilities to 46.5 min for those grid cells farthest away, with an average travel time of 20.29 min. On-road transportation costs varied between 0 and 59.55 \$ (average of 24.4 \$), and considering the a chipvan loading capacity of 25 t, on-road costs per ton ranged from 0.1 to 2.37 \$ t^{-1}, with an average of 0.98 \$ t^{-1}. Total transportation costs, calculated by adding off-road and on-road transportation costs, varied between 0.1 \$ t^{-1} for grid cells immediately adjacent to facilities to 5.48 \$ t^{-1} for grid cells farther away. The average total transportation cost for the entire four-county test area was 1.61 \$ t^{-1}. Fig. 2 shows the spatial pattern of total transportation cost by grid cell across the test area, where cost increased with distance from conversion facilities along the roads network as well as with increasing distance from existing roads. Additionally, transportation costs seemed to increase at a slower rate along major road likely due to the higher speed limits.

3.2. *Break-even biomass amount*

After combining production costs with the biomass price of 40 \$ t^{-1} (dry basis), break-even biomass amount by grid cell was calculated across the test area, with values ranging from 3.49 to 4.31 t yr^{-1} (dry basis). The spatial distribution of break-even biomass amount across the test area directly resembles that of total transportation costs (Fig. 3). This is likely explained because establishment and management, and CCB costs are constant across the test area and variations in production costs are caused only by the location specific on-road and off-road transportation costs. The distribution of break-even biomass amount showed that smaller values occurred on grid cells in close proximity to the existing facilities and/or adjacent to the road network, whereas larger values are associated to grid cells distant from existing facilities along the road network and/or far from existing roads. Consequently, the amount of biomass required to break-even (an

Fig. 3 – Distribution of break-even biomass amount for sweetgum by grid cell.

LEV of zero) is directly related to the total transportation cost. As hauling distance from potential sites to the facilities increases, so did the break-even biomass amount. Similarly, biomass break-even amount increased for grid cells that were located father away from existing roads, making sites located near facilities and/or in areas close to existing roads more desirable.

3.3. Expected biomass yield

Results from site index calculations showed a wide range of values across the test area (Fig. 4). Site index values varied between 18.6 and 28.9 m, with an average of 21.51 m, but as aforementioned, grid cells with site index values below 22.9 m were considered unsuitable for establishing sweetgum (Fig. 4). While all remaining grid cells have site index values that fall within the acceptable low and medium site index classes, no grid cells have site index values large enough to be classified as high site index class. A total of 52,778 ha representing 31.1% of the entire test area were suitable for establishing sweetgum energy crops. Most suitable areas were located in the low site index areas yielding biomass estimates in the range of 3.24–4.54 t yr^{-1} (dry basis). The spatial distribution of these suitable sites showed that more productive sites were mostly concentrated near water along streams (Fig. 5). Even though suitable sites are found throughout the test area, most suitable areas are concentrated in Trimble County and also near the Ohio River along the northwest border of the test area.

3.4. Suitable locations for dedicated energy crops

Break-even biomass amounts were compared with biomass yield estimates in each grid cell to identify suitable sites to establish economically feasible sweetgum energy crops. As aforementioned, break-even biomass amount ranged from 3.49 to 4.31 t yr^{-1} (dry basis) and potential biomass yield ranged from 3.24 to 4.54 t yr^{-1} (dry basis). When overlapping these values and comparing them in each grid cell, a total of 23,786 ha presented biomass yield estimates larger then break-even amounts, making it suitable and economically efficient for establishing sweetgum as a dedicated energy crop. Although these sites are dispersed throughout the test area, most are clustered near riparian areas (Fig. 6a).

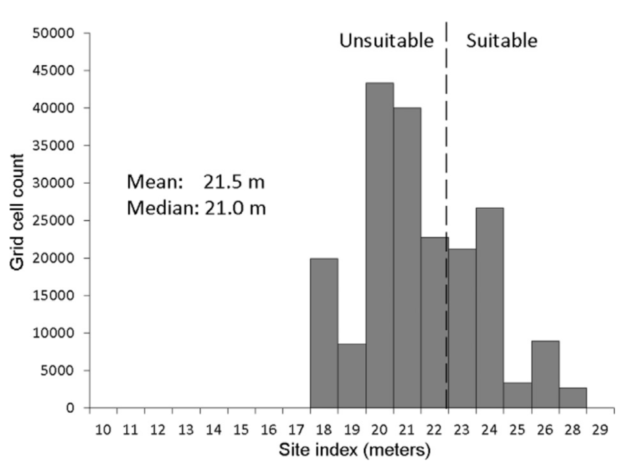

Fig. 4 – Site index distribution for sweetgum across the test area.

To prevent competition with food production and avoid conversion of natural forests, we further restricted our analysis to sites with current land use identified as pasture/hay and barren land types covering an area of about 47,158 ha. After overlaying the spatial distribution of the sites suitable and economically efficient for establishing sweetgum with that of pasture/hay and barren lands, 10,088 ha were identified (Fig. 6b). These sites are scattered throughout the test area, but slightly clustered in eastern Trimble Co., northeastern Carroll Co., and southwestern Gallatin Co. Lastly, if all suitable sites in the test area are converted to sweetgum energy crops, a total potential biomass production of approximately 47,500 t yr^{-1} (dry basis) can be achieved.

4. Discussion

The model was successful at identifying sites where establishing dedicated energy crops may be economically feasible. As both on-road and off-road transportation costs are the only variable cost components, they have a significant effect on the resulting pattern of suitable sites. In general, suitable sites are located relatively close to existing roads and to the existing conversion facilities. However, a large portion of suitable sites were scattered throughout the test area and some were relatively distant from facilities. This is likely because of the favorable site conditions that resulted in biomass yield large enough to cover production costs.

A total of 10,088 ha were identified as suitable and economically feasible to establish sweetgum dedicated energy crops, which represented about 21% of the total available pasture/hay lands in the test area. To meet an increasing demand of biomass for energy production, sites outside this land use might also offer a land base for establishing bioenergy crops. Moreover, government incentives such as tax breaks and subsidies might increase landowners' willingness to grow more bioenergy crops, thus increasing the area available for dedicated energy crops. Similarly, an increase in the delivered biomass price at conversion facilities will also likely encourage landowners to establish bioenergy crops and significantly increase the areas suitable for these crops.

The main limitation of our approach is the large uncertainty associated with the estimation of biomass yields, which is based on site index obtained from SSURGO soil data. Although these data were compiled with the purpose of minimizing discontinuity in map units along soil survey area boundaries, inconsistencies and edge-matching errors are prominent. Despite this fact, the SSURGO database is the most comprehensive soil dataset with the finest resolution available in the US. We estimated potential biomass yield based on data provided by Kline and Coleman [20] derived from expert opinions, but these estimates do not account for management changes (plantation density, range of fertilizer and pesticide application rates) that can increase biomass productivity. Additional management options such as promoting genetic improvements through biotechnology and clonal forestry are also likely to increase biomass productivity. Consequently, biomass yields used in this study are likely to be lower than

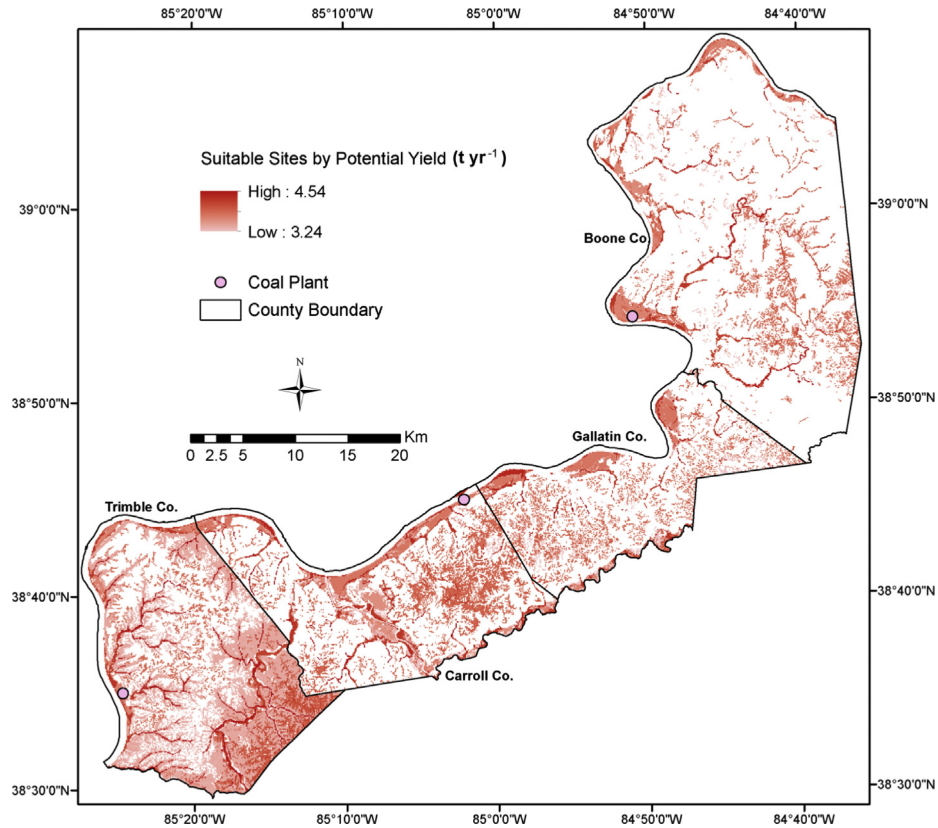

Fig. 5 – Suitable sites for sweetgum energy crops with potential biomass yield across the test area.

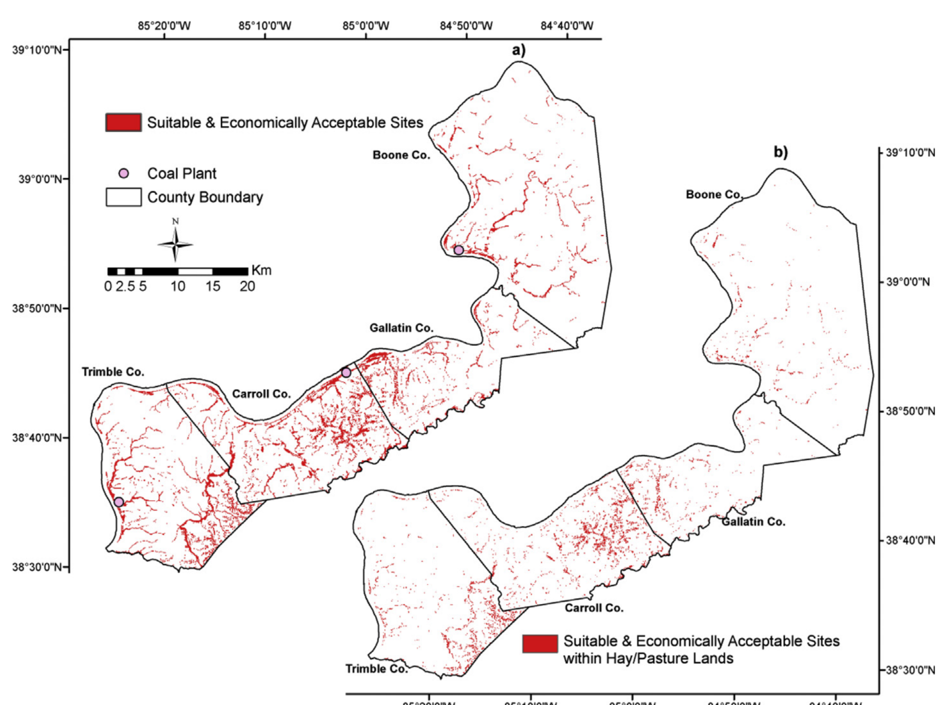

Fig. 6 – Suitable and economically efficient sites for establishing sweetgum across the entire test area (a) and across existing pasture/hay lands (b).

potential productivities under more intense management scenarios.

The species considered in this study was selected following recommendations from Kline and Coleman [20] based on the species growing range, site requirements, costs and potential biomass yield in the southeastern US. However, other short rotation woody crops such as willows (*Salix* sp.), poplars (*Poplar* sp.), and sycamore (*Platanus occidentalis* L.) should also be considered. As aforementioned, establishment and management is the largest cost component in production costs. Other softwood species such as loblolly pine that require relatively lower establishment and management costs due to less site preparation, readily available inexpensive seedlings, and less weed control, also have a great potential to generate positive economic returns. Future research with alternative energy crops and silvicultural and management practices is needed in this region. Furthermore, we considered a 90-m grid cell resolution and assumed it represents an area of manageable size. In practice landowners and managers might require a minimum area in order to cover fixed costs or to meet desired revenue levels. However, the model can be easily adjusted to identify suitable areas with a minimum size instead of individual grid cells depending on the operational constraints associated with potential end-users.

As aforementioned, the model was developed as a general tool that can be applied to any spatial scale and to various geographic regions. Given the availability of input data, it can be applied to evaluate different market conditions and policy scenarios to evaluate their effects on the amount of suitable area. This model can then serve as a useful analytical tool to evaluate alternative production scenarios and identify cost-effective biomass production approaches. Validating this model would further increase its application. However, it was out of the scope of this study because proper validation for this biomass site suitability model would entail establishing, growing, and harvesting dedicated energy crops to determine economic efficiency of potential sites. This validation would require several years and considerable initial investments, especially at relatively large scales. Because our model in essence compares potential biomass yields with break-even biomass amounts derived from production costs, alternatively one can indirectly validate the model by evaluating the accuracy of these two procedures. For example, biomass yield and soil characteristics can be measured in different crops of varying ages to determine the accuracy of the procedure used in our approach and/or to develop more accurate biomass prediction models. Similarly, harvesting and transportation costs can be collected from different biomass harvesting operations to validate the procedure used to determine production costs and evaluate its accuracy.

5. Conclusions

Dedicated energy crops have the potential to provide a stable feedstock supply that supports a sustainable bioenergy industry in Kentucky, but there is limited research identifying suitable sites. In this study, we developed a spatially-explicit model to identify suitable and economically efficient locations to establish dedicated energy crops based on production costs, biomass price, and site productivity. The ability of our approach to address the spatial nature of biomass production economics makes it a useful tool to evaluate how biomass production factors influence the amount and spatial distribution of land suitable to establish bioenergy crops.

Results from our analysis showed 10,088 ha across the four-county test area as suitable and economically feasible for establishing sweetgum energy crops representing about 21% of the total available pasture/hay lands. The spatial distribution of these sites is dependent of production costs and biomass productivity. Break-even biomass amounts are directly dependent on transportation costs as it is the only variable production costs across the test area. The model incorporates not only proximity to conversion facilities (on-road transportation) but also the relative location of potential sites to existing road network (off-road transportation). This increases our ability to more accurately address the spatial nature of production costs and thus biomass production, which to our knowledge has not been incorporated in previous biomass studies.

Although the model application was shown in a relatively small four-county test area in northern Kentucky, it can be applied to larger state or regional scales. As road transportation network data are typically available from transportation departments and/or GIS data repositories and as SSURGO soils data cover the entire continental US, the model has a good potential applicability to different regions where biomass production is recommended. Based on estimates of different silvicultural treatment costs and associated resulting biomass yields for a range of species, the model can be used to select the combination of best species and treatments to maximize biomass yield and reduce production costs. The model could also be used as a decision making tool to conduct sensitivity analysis and evaluate the effect of changes in biomass prices and production costs and other market conditions on the total area suitable for establishing energy crops, their spatial distribution, and the total amount of biomass production. Similarly, this approach could be used to evaluate the impact of different policy incentives and determine the most efficient policy decisions to promote a sustainable biomass industry.

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