Determination of the Optimal Size and Location of an Electricity Generation Plant That Uses Lignocellulosic Residues From Costa Rican Northern

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Abstract

The northern zone of Costa Rica has extensive forestry and agro-industrial development, which generates a large number of lignocellulosic residues that do not have an economic value but could represent a vast energy potential. Therefore, the objective of this study was to determine the optimal size and location of an electricity generation plant from the forest and agro-industrial biomass. The researchers worked with two forest species residues (*Gmelina arborea* and *Tectona grandis*) and two agro-industrial residues (*Anana comosus* and *Saccharum officinarum*), representing the most extensive cultivations in the region. The material was characterized, then GIS layers of the species cultivation areas were analyzed and related to the roads and protected areas to define the twelve potential points where the power plant should be installed. Later the optimal supply radius of the plant and the optimal site conditions were determined. The study determined that the tree species have an average caloric power of 19059.50 kJ/kg, significantly higher than the agro-industrial ones (16684.9 kJ/kg). It was determined that 1,056,527.67 tons of dry biomass are generated per year, 6.5% of the biomass is arboreal, and 79.97% comes from *A. comosus*. Also, it was determined that the optimal supply radius for the plant is 30 km. Longer distances make the project financially unviable. Considering this, the annual energy potential of the twelve points was evaluated, which varied from 4.06 to 101.82 MW. Point eleven was determined the best positioned by the biomass source and optimal environmental conditions for establishing the power plant.

Introduction

Lignocellulosic biomass is defined as dry plant origin material [1], considered a viable alternative energy source to fossil fuels and natural gas [2]. The ease of generation of biomass from agro-industrial and forestry crops, the low CO_2 emission, the simplicity of storage and use and management together with the energy potential of productive residues [3]; make the biomass an optimal energy source for developing countries that have large agro-industrial and productive forestry areas [4]. It is estimated that biomass supplies about 10.4% of world energy demand, and for the next decade, an increase of 16% is expected [5].

Valverde et al. [6] mentioned that biomass could be transformed into electrical energy through thermochemical processes such as combustion, pyrolysis, liquefaction, or gasification, focused on self-sufficiency or energy sale for commercial purposes. The cost of energy from biomass varies related to the technology used and based material. Sometimes its low cost is because residues from a productive system that do not have an economic value are used. If not used for energy production, the residues would be burned, sent to landfills, or buried [7].

Consequently, including them in a sub-process allows improving the efficiency of the material and generating a lower environmental impact, causing economic and environmental benefits in rural communities [8]. Zhang et al. [9] highlight that the residual agricultural biomass for power generation is abundant; For example, about 60% of the sugarcane and rice plant are not used in the production system. Kinoshita et al. [10] emphasize that the tree biomass from pruning or thinning in the first years of cultivation tends to be discarded, which could represent a high percentage of raw material for energy generation.

In order to maintain biomass energy competitiveness against other renewable sources (hydro or thermal) and non-renewable sources (fossil fuels or natural gas), biomass generation must ensure a low financial cost. Sahoo et al. [11] and Sharma et al. [12] highlight that to ensure the competitiveness of this energy source, three main elements must be taken into consideration: caloric power of biomass (heat generation capacity for energy purposes), moisture content of biomass (must be less than 30% for efficient use) and location of the power generation plant from the sources of biomass origin (in order to keep the transportation cost as low as possible). This last variable is the most relevant in reducing costs in biomass generation systems; since the cost of transportation could represent 35% of the final cost of the electricity generation, according to Viana et al. [13] in generation plants in Portugal.

In addition, the quantification of waste products in the productive areas, identifying the areas with greater ease of access, and the installation of biomass processing zones are fundamental factors to determine the potential costs of an energy project [14]. Therefore, Geographic Information Systems (GIS) represents a powerful tool for integrating biomass generation information, simplifying the study, and selecting optimal areas to establish power generation plants [15]. The potential of GIS to relate spatial and productive data has been widely used in the last decade. Shi et al. [16] in Guangdong, China, determined that to have a competitive electricity generation price, the maximum biomass transport distance should be 60 km. On the other hand, in Portugal, Viana et al. [13], using this same technology, determined three specific points for developing a power plant. Hiloidhari et al. [17] in India determined the installation points of biomass reception plants from the road network to create a sustainable biomass production network. Finally, Lozano-García et al. [8] determined the development of areas for energy plantations that could supply an already installed plant in order that within three years, the plant would have a stable source of biomass and that in the process, the existing wild areas would be protected.

Given the potential for using GIS to determine productive biomass areas in Costa Rica, it opens the possibility of creating layers of information that allow planning and sustainable use of biomass as a long-term energy source. However, there are no clear studies that implement GIS in the tropical region to optimize power plants. Therefore, in the present study, the size and optimal location of an electricity generation plant from the forest and agro-industrial biomass in the northern zone of Costa Rica was determined.

Materials And Methods

Study site and crops

The study was carried out in the northern zone of Costa Rica (10°20'- 11°48' N) and (84°10'- 85°26' W), which has an area of 7030.86 km^2 and is characterized by a wide productive agricultural and forestry development. The annual temperature varies between 28°C and 32°C, the annual relative humidity varies from 60–95%, with an annual rainfall of 1800 mm to 4200 mm and a rainy season of seven months distributed from May to November.

This study analyzed residues of forest and agricultural crops left in the field due to management and harvesting activities. At the forest level, the two forest species with the most significant area planted in the zone were analyzed: *Gmelina arborea* and *Tectona grandis*. The georeferenced information used for both species was based on the National Forest Inventory of 2014. In agro-industrial crops, greater economic importance and more significant extension in the area were analyzed, represented by *Anana comosus* (pineapple) and *Saccharum officinarum* (sugar cane). For *A. comosus*, it was implemented the georeferenced layer (GIS) of crop distribution developed by PRIAS in 2019, while the information of *S. officinarum* came from the study of Chaves and Chavarría [18].

Biomass estimation at the study site

Field sampling was conducted to determine the amount of biomass waste generated by the crops. From the information obtained through the GIS layers, twelve sites per crop were selected, and random sampling was developed. In each site, six rectangular plots of 100 m^2 were established, in which all the biomass considered as the residue was weighed in the case of forest species, all the remaining branches and trunks from pruning and thinning, and for agro-industrial crops, all the residues from handling and harvesting. A sample composed of 500 g of biomass was taken from each site and estimated the caloric power, moisture content, and ashes.

Determination of caloric properties and humidity of the study crops

From each crop, a sample composed of 500 g of material was collected. The sample was pulverized with a mill and then used to determine caloric power, moisture content, and ashes. The caloric power analysis was developed under the ASTM D-5865 standard [19], which proposes to dry the material in the furnace for 48 hours and later to sift it to generate a particle size of 0.25 to 0.52 mm, from which three subsamples of 5g of material were extracted. In order to have representative data of each analyzed waste, we worked with the triplicate mode.

The moisture content was determined through the ASTM D-4442 standard [20], weighing the twenty samples of residues in green condition and drying them in an oven for 24 hours at a temperature of 103°C. This generated the dry weight that was used in Eq. 1 for the calculation of the moisture content. Finally, the ash content was determined with ASTM D 1102-84 norm [21].

$$MC = \frac{GW - DW}{GW} x100 \text{ (Equation 1)}$$

Where: MC is Moisture content (%), GW is Green weight (g), DW is dry weight (g).

Determining the optimal location of the power plant.

Due to the region's expanse and many potential locations for the electric power plant, a pre-selection of twelve points that presented the possibility of meeting the minimum conditions for installing the infrastructure was developed (Fig. 1). The elements considered in this selection were: i. access to public roads, ii. proximity to industries with potential energy demand, iii. distance to electricity generation projects that represent direct competition, and iv. proximity to towns.

Determination of the optimal biomass supply distance

From the twelve potential locations for the power plant, the maximum biomass supply distance was analyzed, by which the available biomass was determined for each point in radius every 10 km with a range of 10 to 100 km, using the average data. Subsequently, the cost of transporting biomass was calculated, referencing the value of the Costa Rican market for transporting dry biomass, which is USD 0.70 ton/km. Therefore, at the national level, the sale price of biomass on-site is USD 62/ton with a maximum transport cost margin of 40%, the same value used in the study as the maximum cost margin to determine the maximum distance [1].

Variables for determining the best plant location

In order to determine the optimal location of the power plant, two fundamental elements were considered: the available volume of biomass and the environmental conditions for the development of the project. Therefore, both elements were evaluated in each of the twelve potential locations established in Fig. 1 using Eq. 2. The potential for plant location was evaluated with a scale from 1 to 100, where values close to 1 show impossibility to develop the plant and values close to 100 considered the project viable. In addition, using a combustion process with a second-generation combustion plant for mixed dry biomass processing was considered [22].

$$MC = \frac{GW - DW}{GW} x100 \text{ (Equation 1)}$$

Where: Ppp is Power Plant Potential, Vb is Volume of Biomass Available, Cp is Conditions for Project Development

Information management

The crops information layers, together with the determination of the supply distances and the power plant's optimal location, were carried out in the program Q GIS version 3.1.4. As for the homogeneity analyses within the data of moisture content, calorimetry, ash, and characterization of the site, an analysis of variance (ANOVA) with a significance of 0.05 was carried out, using the program R version 3.6.2 [23].

Results

Characterization of the caloric properties of the residues

The characterization of the caloric properties presented a variation between forest biomass and agro-industrial biomass (Table 1). The caloric power of *G. arborea* and *T. grandis* showed an average value of 19059.50 kJ/Kg. *comosu*s and *S. officinarum* was 16684.9 kJ/Kg. As for the moisture content, the forest species presented an average value of 80.33%, a lower value than the agro-industrial crops, which was 90.22%. Finally, no significant differences were found in the ash content between the four crops, showing an average value of 5.31%.

Table 1
Calorimetric assessment of forest and agro-industrial crops with biomass generation potential in the northern zone of Costa Rica.

Biomass type	Caloric power (kJ/kg)	Moisture content (%)	Ash (%)
G. arborea	18518.3 a (368.4)	81.53 b (9.44)	4.34 a (2.11)
T. grandis	19600.7 a (690.0)	79.13 b (9.89)	3.99 a (1.02)
A. comosus	17189.3 b (789.9)	92.30 a (7.34)	5.90 a (1.23)
S. officinarum	16180.5 b (867.6)	88.14 a (8.87)	6.99 a (1.53)
Note: values in parentheses correspond to standard deviation.			

The energy capacity of available biomass

When analyzing the generation of residual biomass (Table 2), it was determined that forest cultivation generated 16.5 ton/ha, which comes from the branches cut in the pruning processes, treetops, and trees that do not meet the minimum harvest diameters. With this, it is possible to find annually about 68 585.5 tons of residual biomass, representing in power the base of an electrical generation of 16.32 MW.

Table 2
Availability of dry biomass with potential for use in electricity generation in the northern zone of Costa Rica.

Biomass type	Dry residues generated (tons/ha/year)	Cultivated area (ha)	Available dry biomass (tons/year)	Energy potential (MW)
Forestry	16.5 (3.2)	4 156.70	68 585.55 (13 301.44)	16.32 (2.96)
A. comosus	34.1 (5.6)	24 794.72	845 500.00 (13 8850.42)	153.72 (28.34)
S. officinarum	24.6 (5.9)	5 790.33	142 442.12 (34 162.97)	26.37 (7.11)
Total	-	34 921.75	1 056 527.67	196.41
Note: Parentheses corresponds to standard deviation.				

In the case of *A. comosus*, the annual generation per hectare of dry residual biomass was 34.1 tons, coming from the handling and harvesting of the crop (the whole plant becomes a residue). These data annually represent 845,500 tons of dry biomass, which currently have no productive use (burned or buried). On the other hand, its use for the production of electrical energy could represent 153.72 MW. Finally, *S. officinarum* generated 24.6 tons/ha/year of residual biomass, coming from harvest residues such as the plant leaves. Taking advantage of these residues could mean an annual contribution of 26.37 MW to the national electrical system.

Determining the optimal radius of biomass supply.

When analyzing the optimal biomass supply radius for the proposed power plant (Fig. 2), the trend was that generation increased as the radius increased (due to increased biomass). The increase was 5% per kilometer; additionally, the same behavior was evident for the cost of transportation, with increases between 7% and 9%. Therefore, the maximum distance of biomass supply in a profitable way was 30 km, since greater distances would generate increases in transport cost that would only be justifiable with a decrease in the profit margin of the sale of biomass or increase in the market values of biomass.

When visualizing the points with the potential areas of biomass supply (Fig. 3), it was shown that 91% of the region under study was covered, taking into account areas where the zones overlap, which can generate errors in the estimation of biomass. To prevent this situation, in the selection processes, very close points should be avoided. In addition, it was noted that the western sector of the region was where there is a greater concentration of biomass but without forestry or agroindustrial development.

Optimal location of the bioelectric generation plant

In the analysis of the biomass availability in the 12 pre-selected points for the installation of the power plant (Table 3), it was determined that the availability of biomass varies between 19897.5 ton/year and 498 906.8 tons/year, and the capacity of electricity generation between 4.06MW to 101.82 MW. Point 11 was the one that presented the highest presence of biomass (especially from *A. comosus and S. officinarum*).

Table 3
Energy potential and available biomass at each potential point for establishing a power plant from lignocellulosic biomass in the northern area of Costa Rica.

Point	Forest biomass (tons/year)	*A. comosus* biomass (tons/year)	*S. officinarum* biomass (tons/year)	Available biomass (tons/year)	Energy potential (MW)
1	11385.2	43966.0	356.1	55707.3	11.37
2	3772.2	71022.0	0.0	74794.2	15.26
3	2126.2	37202.0	3789.0	43117.1	8.80
4	6309.9	173327.5	7976.8	187614.1	38.29*
5	1783.2	37202.0	0.0	38985.2	7.96
6	8641.8	27901.5	1709.3	38252.6	7.81
7	19821.2	180091.5	1566.9	201479.6	41.12
8	4197.4	18601.0	0.0	22798.4	4.65
9	1714.6	17755.5	427.3	19897.5	4.06
10	754.4	151344.5	9543.6	161642.6	32.99
11	823.0	408630.2	89453.7	498906.8	101.82*
12	3840.8	131898.0	71078.6	206817.4	42.21

In the case of points 7, 10, and 12 (with the generation of 32.99 to 42.21 MW), the high energy potential is due to the overlap of the radius compared to the area of point 11. If the overlap were eliminated, the energy potential would decrease from 35–65%. On the other hand, site 4 was the only point where there was no overlap with point 11, and it also had a high energy potential (38.29 MW).

When analyzing the distribution of biomass in the pre-established points, the wide distribution of forest biomass and *A. Comosus* was noted, with the biomass of *S. officinarum* being the most restricted (absent in points 2 and 5). It was only the primary energy source in forest biomass in point 7, slightly exceeding agro-industrial crops. In the remaining points, the high presence of *A. comosus* was significant, and the fact that its distribution is closer, which allowed the creation of harvesting clusters.

By analyzing the conditions for establishing the plant at each site (Table 4), with the road network, only points 3, 4, and 6 showed significantly lower values because they were in areas with ballast roads, while the rest of the points were asphalted. The electricity network connection in points 1, 3, 4, 5, and 6 presented supply problems due to their distance from the distribution networks, which would require the installation of connection towers that would increase the project's costs.

Table 4
Potential values analyzed to establish an electricity generation plant from lignocellulosic biomass in the northern zone of Costa Rica.

Point	Road network conditions	Electrical network connection	Closeness of towns and industries	Industry growth potential	Distance to conservation areas	Total
1	15.3 a (1.2)	10.2 b (1.1)	12.2 b (1.5)	18.8 a (2.3)	16.5 a (1.2)	73.0
2	14.4 a (1.2)	12.2 a (1.2)	13.5 b (1.4)	17.7 a (2.4)	14.4 b (1.4)	72.2
3	8.5 c (1.2)	8.4 c (1.1)	17.7 a (1.6)	12.5 a (2.5)	8.8 c (1.3)	55.9
4	12.2 b (1.4)	9.3 c (1.3)	18.8 a (1.3)	14.4 a (2.5)	12.2 b (1.2)	66.9
5	14.4 a (1.2)	11.1 b (1.2)	16.6 a (1.5)	13.3 a (2.4)	20.0 a (1.3)	75.4
6	11.1 b (1.2)	12.2 b (1.0)	16.7 a (1.8)	11.5 a (2.4)	17.8 a (1.4)	69.3
7	13.3 a (1.3)	16.9 a (1.1)	18.9 a (1.4)	18.8 a (2.3)	16.6 a (1.4)	84.5
8	17.6 a (1.2)	18.0 a (1.2)	17.0 a (1.3)	16.0 a (2.2)	20.0 a (1.5)	88.6
9	18.8 a (1.1)	19.0 a (1.2)	17.1 a (1.6)	15.7 a (2.2)	18.2 a (1.2)	88.8
10	16.6 a (1.1)	19.0 a (1.3)	18.8 a (1.7)	15.6 a (3.2)	16.6 a (1.4)	86.6
11	17.9 a (1.1)	19.0 a (1.1)	18.8 a (1.5)	13.3 a (2.2)	18.2 a (1.5)	87.2
12	16.9 a (1.2)	18.4 a (1.0)	19.9 a (1.6)	14.4 a (2.2)	11.3 b (1.4)	80.9

Note: Parenthesis value is standard deviation. Different letters show statistical significance at 0.05.

Regarding the variable proximity to towns and industries, only points 1 and 2 showed statistically lower values due to the remoteness of towns and industries. In addition, no significant differences were found in the growth potential of industry between the twelve points of study, which presented conditions for the increase of agro-industrial activities. Finally, points 3, 4, and 12 presented proximity to protected areas, which meant that lower scores were given in the assessment.

When establishing the optimal installation point of the power plant (Table 5), it was determined that point 11 (Fig. 4) had the ideal environmental conditions and enough biomass for the installation of a bioelectricity generation plant. Then, points 7, 10, and 12 were found as sites with installation potentiality higher than 52%, with the limitation that they overlapped areas with point 11. Therefore, the three points' energy potential was reduced from 22 to 45% by eliminating the overlapping area. Later, point 4 was found to have a potentiality of 49.32% and not overlap with point 11. The other points had feasibility of less than 40% for the installation of the plant, which was considered not very viable for its development.

Table 5
Values of biomass availability and potential for establishing a power plant from lignocellulosic biomass in the northern zone of Costa Rica.

Point	Biomass availability (%)	Site conditions (%)	Total (%)
1	6.69	29.20	35.90
2	8.99	28.88	37.87
3	5.18	22.36	27.55
4	22.56	26.76	49.32*
5	4.68	30.16	34.85
6	4.60	27.72	32.32
7	24.23	33.80	58.03
8	2.74	35.44	38.18
9	2.39	35.52	37.91
10	19.43	34.64	54.08
11	59.99	34.88	94.88*
12	24.87	32.36	57.23

Discussion

Biomass conditions for electricity generation.

The study determined that the biomass of the four species exceeded 15000 kJ/kg. According to Ogorure et al. [24], this was considered high energy capacity biomass, thus allowing the energy use with the limitation that the moisture content was above 80% in all species. This makes it necessary to develop a drying process of the biomass so that the humidity of the biomass was less than 30% and the combustion process was acceptable (humidity contents higher than 30% decrease between 40 and 60% the energetic capacity of the biomass [25]. Furthermore, Kosse et al. [7] recommend placing the bioelectric plant close to the biomass generation areas to decrease the cost of transporting wet biomass (which would increase the generation costs). Kaundinya et al. [26] mentioned that biomass generation should be developed with low-cost processes of moisture homologation, either with solarization techniques, the use of gases or heat from boilers, and an increased storage period of biomass.

Another important element to consider is the use of biomass was the size of the material to be contributed to the boiler. Since the biomass understudy was so varied (forestry and agro-industrial), it would require a transformation process, either in pellets or particles, so that the biomass was as homogeneous as possible, and thus the combustion process was continuous. Ogorure et al. [24] mentioned that in the generation of bioelectricity, the homogeneity of the size of the particles is fundamental so that the energy consumption of combustion does not increase, and with it, the boiler's performance decreases. According to Farrell et al. [25] this is fundamental in the design and development of boilers. The boiler is designed for optimal combustion performance according to the material. Using heterogeneous materials will decrease energy productivity by 5–40%.

Importance of biomass distance in power plants

The range of biomass supply to the power plant is a relevant factor when selecting the location of the facilities. In sites with a dispersed distribution of biomass, such as the study region (Fig. 1), the range of supply was relevant to the energy project: areas with low biomass availability will either decrease generation or increase the supply area so that biomass transportation costs will increase. Kinoshita et al. [10] and Flores-Marco et al. [27] mentioned that the installation of the plant should consider the lowest displacement of the raw material. To reduce costs, make a planned process in which biomass availability is constant over time, and the impact on roads and towns is minimal. Dalla-Longa et al. [28] emphasized that the biomass near the power plant simplifies transport planning, increasing the volume of biomass transported daily, which would impact the need for less investment in biomass storage. This can generate a decrease in the fixed costs of electricity generation. The defined distance of 30 km (Fig. 2) was a contrast to Jayarathna et al. [22], who recommended 100 km, and Viana et al. [13] with 35 km; the differences are due to the electricity and transportation costs of each country in addition to the maximum available energy capacity of the regions under study.

GIS in determining optimal power plant points

Georeferencing the areas of biomass production, knowing the capacity of waste generation in conjunction with aspects such as electrical connection, road network, and conservation areas allows the definition of optimal areas for the establishment of power generation units. Höhn et al. [29] and Kaundinya et al. [26] emphasized the need to have multivariate information for decision making in power plants in order to count the most significant number of technical criteria at the time of installation of a plant and avoid errors in location or consideration of ease of energy sources or electrical connection, for the study area with its wide dispersion of biomass sources, being able to select an area of high productive concentration allows not only to generate more electricity production but also to reduce the costs of generation by transport.

Zyadin et al. [15] and Jeong, & Ramírez-Gómez [30] highlighted that having geospatial data concerning energy productivity for the tropical region allowed knowing the areas of energy accumulation bioenergy processes should be a priority. It also defined possible biomass storage points and areas of low intervention due to low productivity. For its part, Yoshioka et al. [31] mentioned that the dimensionality that generates the georeferenced information allowed the optimization of the logistics of biomass movement and defined the shifts of harvesting and collection of material. This prevented regions with abrupt topography or infer in low yields and decreased the ability to define priority areas. Teixeira et al. [32] in Portugal determined that the possibility of defining the regions with the highest concentration of biomass allowed for the design of power plants that have an appropriate capacity and categorize the areas according to energy priority, which avoids investing in low productive or high-cost areas.

Conclusions

It was determined that the tree species of the study have an average caloric power of 19059.50 kJ/kg, significantly higher than the agro-industrial ones of 16684.9 kJ/kg. Furthermore, the moisture content in the arboreal species is 80.33%, and for the agro-industrial crops, 90.22% with an average ash commitment of 4.16%. In terms of biomass generation, the study area generates 1 056 527.67 tons annually, with *A.comosus* generating the most significant biomass representing 79.97%, while forest species only 6.5%; enough biomass to generate 196.41 MW of electricity.

About the area of biomass supply for the power plant, it was determined that the maximum radius of consumption is 30 km since larger radiuses are financially unsustainable. Therefore, the optimal point was found to be point 11, located in the southeast of the region, which can generate 101.82 MW annually, and which has the best conditions in the region in terms of accessibility to roads, electrical connection, proximity to towns, and industry, growth potential, and distance from conservation areas.

Declarations

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Availability of data and materials

The data analyzed in this manuscript are available from the corresponding author upon request.

Authors ‘contributions

JCV, DA and RC developed the concept of the study; JCV, CM, MF and LB collected the information; JCV performed the statistical analyzes; all authors participated in the writing and proofreading of the article.

Ethics approval and consent to participate

All the authors have actively participated in the publication. They agree on the information provided and that ethical standards have been respected in the generation of the information. They also agree to be part of the authors of the article.

Consent for publication

All authors agree with the publication of the manuscript according to the journal's policies. They have accepted the observations given and respect the associated regulations for the publication of the research.

Competing interests

The authors declare that they have no conflict of interest.

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Figures

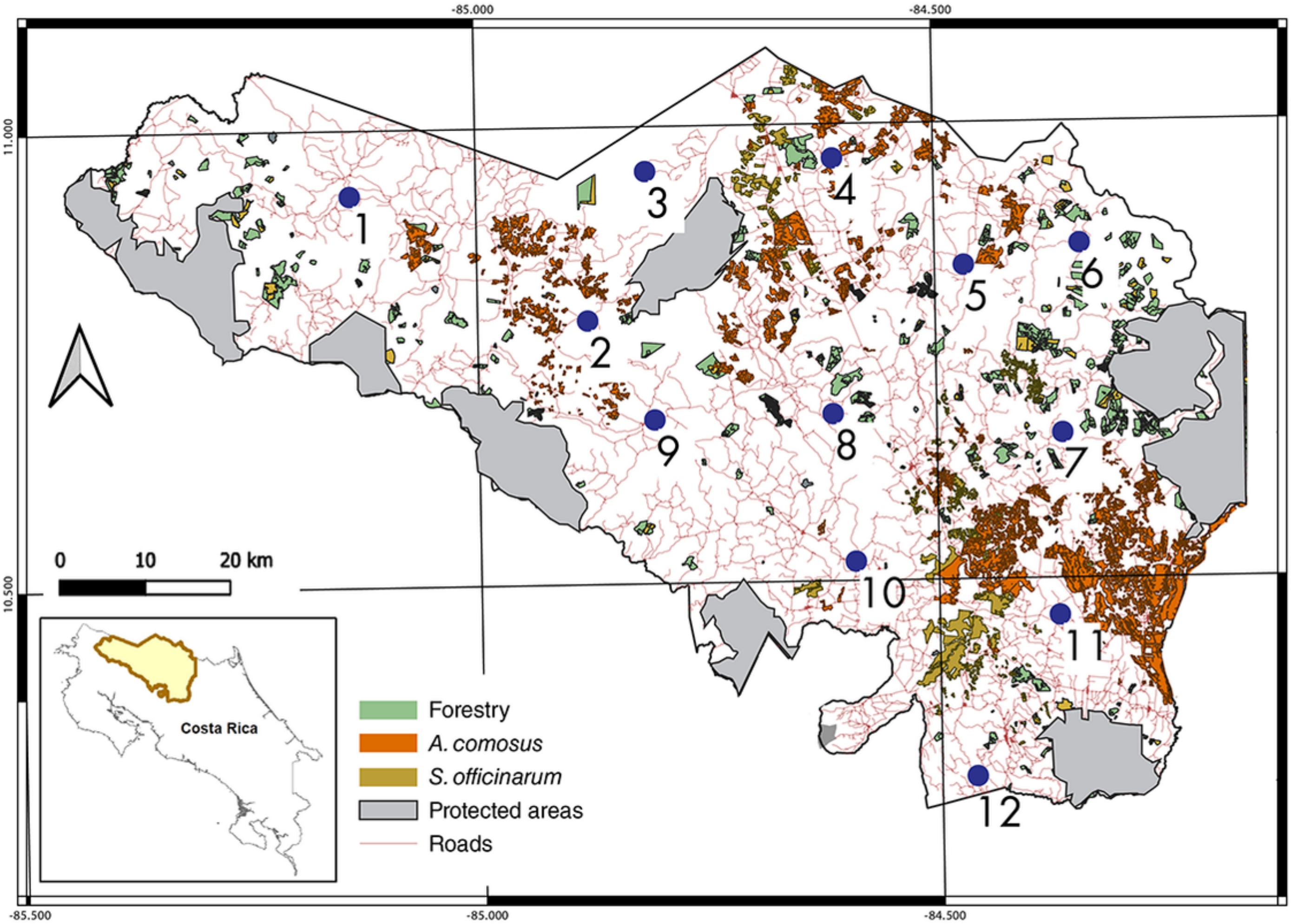

Figure 1

Forest and agro-industrial coverage and pre-selected points for establishing an electric generation plant from residual biomass in the northern zone of Costa Rica.

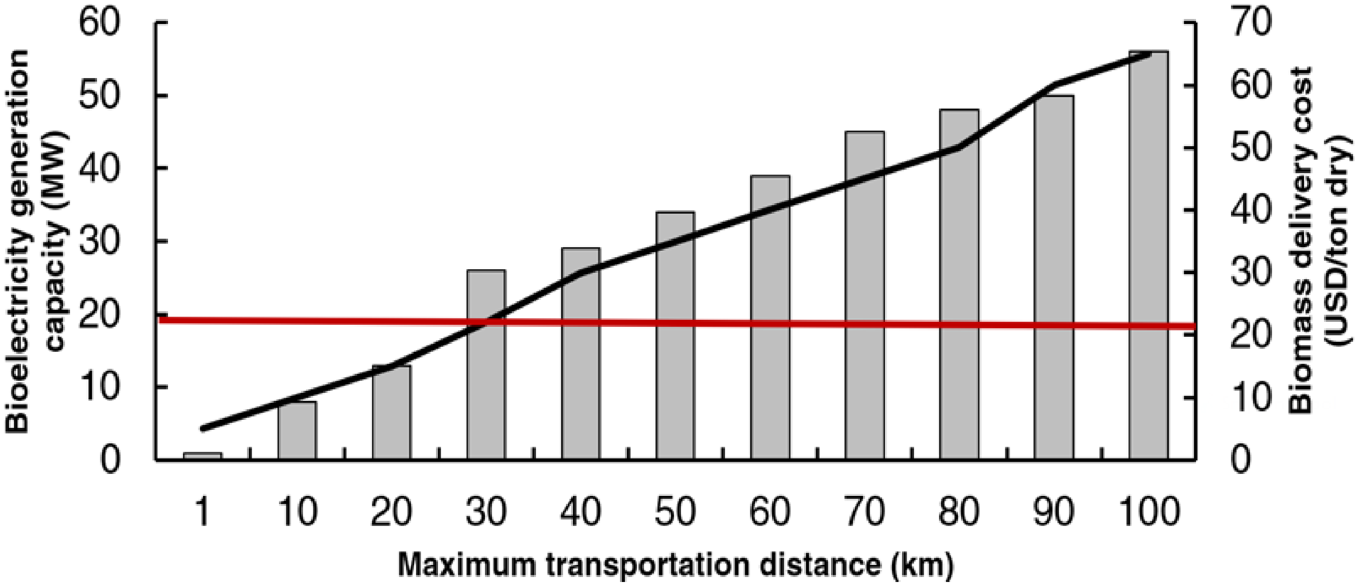

Figure 2

Determination of the maximum radius of lignocellulosic biomass transportation as a function of bioenergy generation capacity and biomass transport costs.

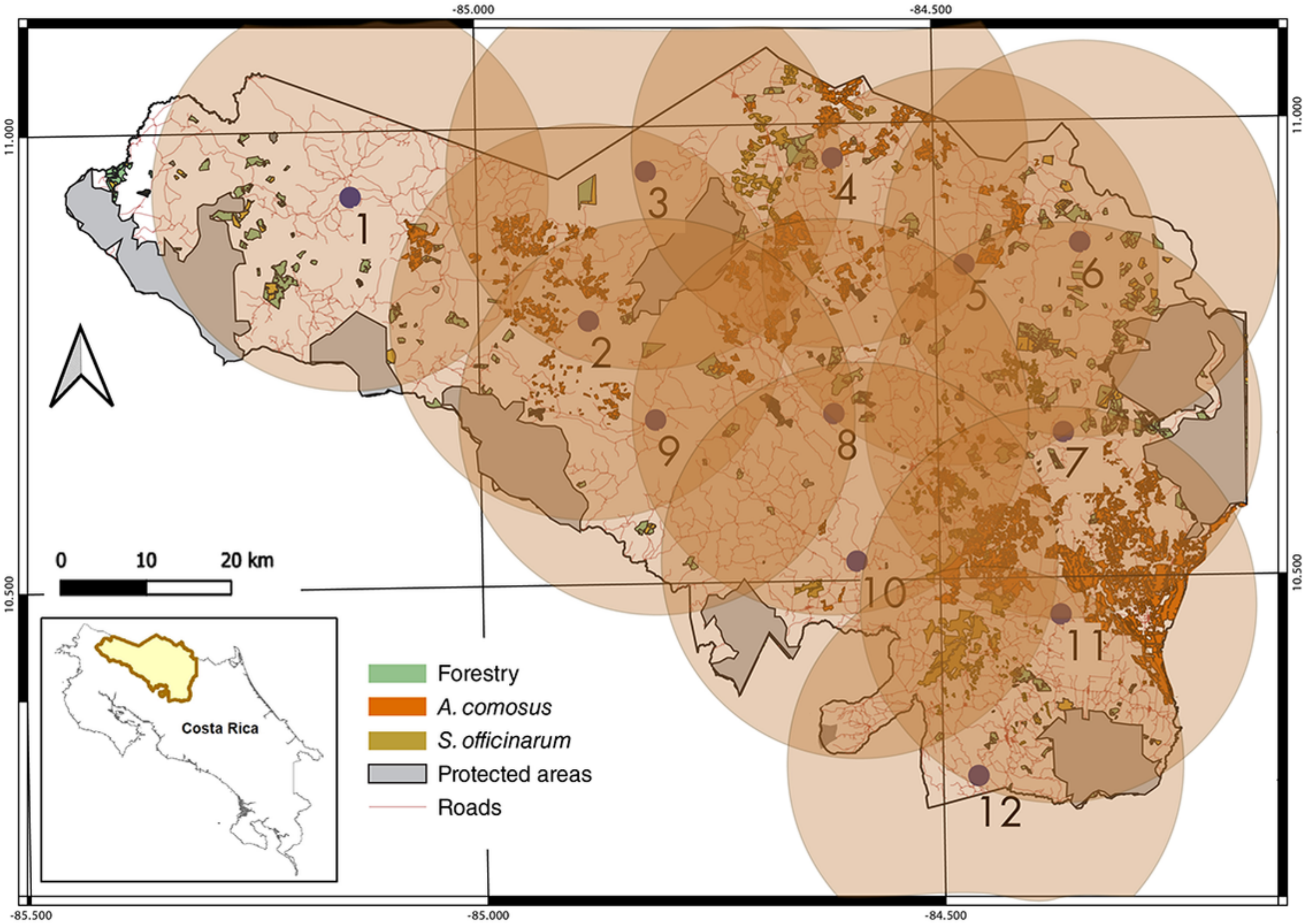

Figure 3

Pre-selected points and radius of biomass supply were analyzed for establishing a power plant using lignocellulosic forest residues and agro-industrial species in the northern zone of Costa Rica.

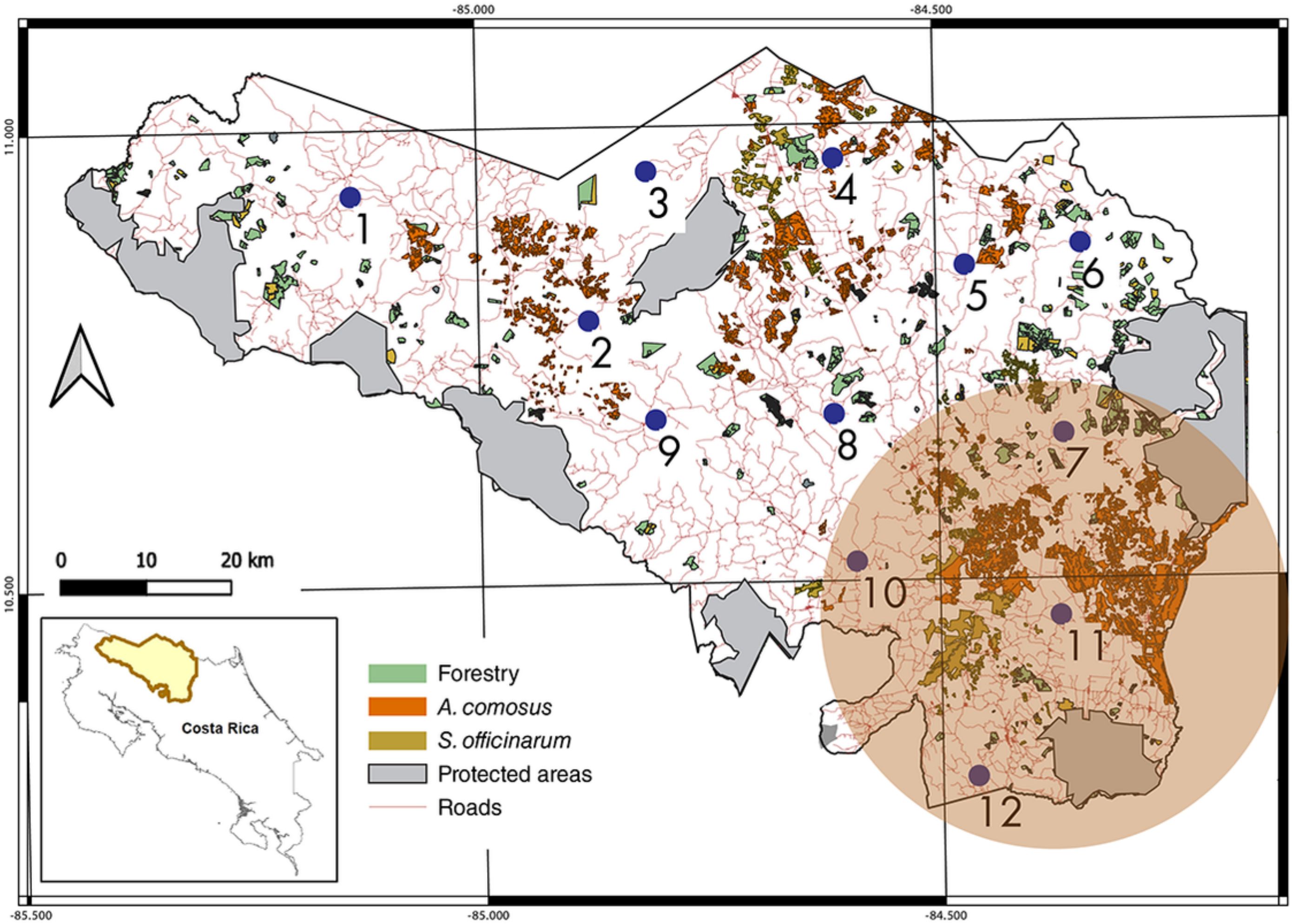

Figure 4

Optimal location and supply area for the installation of a power plant from lignocellulosic biomass in the northern zone of Costa Rica.