A Hierarchical Approach to Estimate Spatially Available Potential of Primary Forest Residues for Bioenergy

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One of the major steps in setting up a bioenergy utilization system is to determine the potential availability of forest biomass. This study illustrates the methodology of estimating the spatial availability of primary forest residues in naturally occurring brutian pine forests, which are considerable components of forest biomass. A spatial database system was created to respectively calculate the theoretical, technical, and spatially economical biomass potentials that were subject to limitation by stand ages, forest functions, site indexes, slopes, and distance zones. To quantify primary forest residues (PFR), the conversion rates were processed, ranging from 24.1% to 26% of allowable cut volume for early thinning, 15 to 20% for thinning, and 11.1% for final felling. The results showed that the total accumulation of theoretical primary forest residues was 86,554.7 green tons in 10 years' time, 71% of which could be ecologically available. Furthermore, the spatially available biomass potential was 6,095.4 tons *per* year within a radial distance of 30 km. In the future, the proposed hierarchical process can be applied to brutian pine stands in the Mediterranean region using a larger dataset that will provide a truer representation of the regional variation.

Keywords: Primary forest residue; Available potential; Biomass; Bioenergy; Supply possibility

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INTRODUCTION

Forest biomass is becoming increasingly important worldwide as a renewable energy source in both industrialized and developing countries. Recent trends in woody biomass utilization involve producing heat and power to expand upon our knowledge of the available biomass potential so that it can be used in a sustainable manner. Determination and estimation of potential woody biomass resources influence investment, procurement, and total utilization costs significantly. Therefore, the most key and foremost step in the concept of forest biomass utilization is to determine the forest's potential. In addition, the type of forest biomass is also important, as it leads to considerable variances between the estimates of biomass potentials (Biomass Energy Europe 2010).

On a wood-based fuels basis, forest biomass is defined as the total amount of roots, stumps, stems, limbs, barks, needles, tops, and leaves of all live and dead trees above and below the ground in a forest (Hakkila and Parikka 2002; Röser *et al.* 2008). Additionally, definitions of forest biomass also typically refer to a wide range of products derived from forests (Eker *et al.* 2013; Saraçoğlu 2010), which contain wood-based products including main stems, small-diameter trees, residues (primary, secondary, and tertiary), and traditional firewood (Berndes 2001). Woody biomass classification is useful to describe the forest biomass utilized as energy wood. This classification system consists of products with high value, low value, and those with value added or minimal value (logging residues, thinned slash materials, *etc*.) (Pincus and Moseley 2009; USDA 2013). Low-value (third class) and minimal-value (fourth class) forest products have become targeted raw materials in the bio-energy sector as energy wood (Eker 2012). This study targeted the logging residues and un-marketable stems of small-diameter trees as primary forest residues (PFR), which can be considered as energy woods. PFR, particularly logging residue, is the woody biomass that is left unexploited in a forest (Daystar *et al*. 2014) that needs to be removed from the forest due to its flammable nature.

Various methodologies and approaches have been developed and used in practice to quantify and estimate the potential of the biomass, depending on the type of woody biomass. The biomass potential type is an important parameter to set data requirements as well as to select an appropriate approach and methodology in determining biomass resources (Biomass Energy Europe 2010). Theoretical, technical, economic, and implementation potentials are considered to be the types of woody biomass potential (Biomass Energy Europe 2011; Böttcher *et al*. 2012).

The results of the biomass availability studies vary depending upon the approach and methodology employed in addition to external (*i.e.* biomass categories, type of biomass, type of potential, time frame, and geographical coverage, *etc*.) and internal (*i.e*. approach, method, terminology, data sources, units, and conversion factors, *etc*.) factors (Böttcher *et al*. 2012). For the feasibility studies, certain techniques have been developed to estimate and calculate the supply potential of the whole forest biomass to be used for energy. Yoshioka and Sakai (2005) and Aruga *et al*. (2006) improved the techniques to estimate the harvesting volume and cost of logging residues in sub-compartments of forests at the regional level. Yamamoto *et al*. (2010) developed techniques using the physical distance from a unit to the end-user. Ranta (2005) developed a technique to obtain the resource allocation of forest biomass using Geographic Information System (GIS) at the national level. Yamaguchi *et al*. (2013) estimated the annual supply potential and the availability of timber and logging residues in profitable sub-compartments for all consumption points based on forest management records and destination locations. The aforementioned techniques used to estimate the forest residue availability potential include various parameters (harvesting volume, supply cost, and revenues.) at sub-compartment and national levels. However, the physical distance is also an important parameter for determining the supply cost of the PFR in energy generation from forest biomass (Kumarappan and Joshi 2014). Therefore, available potential can be estimated by spatially explicit analysis. GIS software has been used in taking inventory, planning, management, and control of forest biomass utilization (Beccali *et al*. 2009; Çoban and Eker 2012; Graham *et al*. 2000; Viana *et al*. 2010). Nevertheless, rapid determination of available biomass potential is a valuable process for engineers, suppliers, and investors.

Forest residue potential has primarily been estimated from standing tree volume or growing stock tables and is approximately 3 million cubic meters, according to General Directorate of Forestry (GDF) statistics in Turkey. Furthermore, some studies also estimated the quantity of forest residues at local or regional levels; however, such studies neglected to estimate both the potential and spatial distribution (Durkaya *et al*. 2009; Eker 2011; Eker *et al*. 2013; GDF 2009; Saraçoğlu 2010). There are only a few models or methodologies that are based on spatial allocation, biomass quantity at regional levels, or possibility to transport from allocation centers located at a reasonable distance that uses forest inventory data.

Biomass studies for the purpose of energy generation have recently gained importance in Turkey. Within the framework of the energy generation strategy developed by GDF that manages the state forests (99.9% of all forests in Turkey), brutian pine trees are the priority tree species to generate energy from the biomass because they are abundant, grow rapidly, and have a high proportion of branch woods. Brutian pine forests account for 27% of the total forest area and 22.6% of the total growing stock in Turkey, while approximately 29.9% of the annual allowable cut volume is obtained from the brutian pine forests (Forestry Statistics 2012). Therefore, this study focused on determining the potential of the primary forest residues in the brutian pine forests. Within this scope, the objective of this study was to develop a feasible estimation model for available potential depending on the theoretical, technical, ecological, and economical capacity of PFR as well as to introduce a methodology based on spatially explicit methods using GIS.

MATERIAL AND METHODS

Study Site and Data Set

The study site is located in the Isparta Forest Region (IFR), lying to the north of the Mediterranean Region of Turkey. Figure 1 presents the spatial distribution of the standing tree volume (m^3) in the brutian pine stands. The study site has a rugged terrain. It is located at an altitude of 70 meters to 2270 meters above sea level. Brutian pine (*Pinus brutia* Ten.) is a dominant species in this region. The pure brutian pine forests occur widely in more than 47% of the whole forest area in the study site, while the rest of the forests consists of mixed or deciduous species (Table 1). Table 1 summarizes the distribution of the total area and standing tree volume of the forests in the study site according to the forest structure and the other characteristics used as reduction criteria.

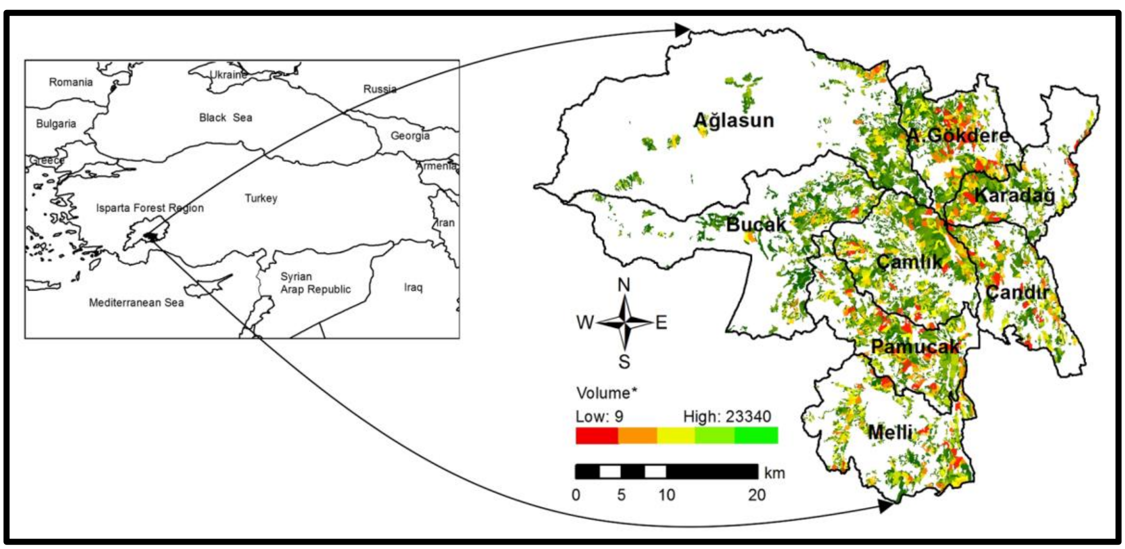

Fig. 1. Location of the study site (*standing tree volume (m^3) for pure brutian pine stands)

The brutian pine forests analyzed in this study has a rotation period of 60 to 80 years, while the majority of the round woods are produced mainly from final cutting and thinning treatments. The woody biomass utilization for energy generation starts at the sapling stage. The timing and intensity of the silvicultural treatments vary depending on the site characteristics (site index) and development stage of the stand (Esteban *et al.* 2008). Therefore, the available PFR quantity also varies (Table 2).

Table 1. Distribution of Total Area and Standing Tree Volume by Study Site Characteristics

Characteristics	Classes	Total area (ha)	Standing tree volume (m^3)
Forest structure	Pure brutian pine	59,111.1	8,342,488.1
	Mixed brutian pine	3,389.9	499,129.7
	Other tree species	63,023.4	919,619.1
	Non-forest	44,454.3	-
Forest function	Economy (Production)	38,167.2	6,244,050.3
	Ecology	9,990.7	1,841,611.4
	Social	1,801.2	256,826.4
Site class	Very good and good (1 and 2)	43,861.5	7,608,590.5
	Moderate (3)	6,097.6	733,897.6
	Low (4 and 5)	-	-
Terrain slope	Low slope (< 31 %)	13,334.8	2,08,9464.2
	Moderate slope (31-60%)	33,407.4	5,697,462.3
	Steep slope (> 60%)	3,216.9	555,561.6

Table 2. Relationship between Silvicultural Treatments and Stand Development Stages in Brutian Pine Forests

Rotation Period	60 to 80 years (It is variable according to site index.)					
Stand Development Stages	Establishment (Seedling) stage	Sapling stage	Pole stage	Thin Timber stage	Medium Timber stage	Thick Timber stage
Average Dbh[1] (cm)	< 7.9		8 – 19.9	21 – 35.9	36 - 51.9	> 52
Silvicultural Treatments	Cleaning[2]	Early thinning[3]	thinning[4]		Thinning or Final felling[5]	

[1] Diameter at breast height
[2] Cleaning is the first release treatment applied to a new stand after establishment.
[3] Early thinning is a treatment applied during the sapling stage following the crown closure.
[4] Thinning is an intermediate cutting made in immature stands for commercial purposes.
[5] Final felling is a regeneration cutting at the end of rotation period.

Cleaning is only applied to young stands where woody biomass cannot be produced because of low energetic contents of the fine materials (Eker *et al*. 2013); therefore, these stands were ignored in this study. About 40 to 60% of the standing tree volume is removed during the early thinning treatments depending on the stand structure. The removed fractions are usually thin and thus rarely used as leaf and chipboard wood. A maximum of two 1m-long roundwoods with small diameter (< 8 cm) can be obtained from each individual traction that is removed. The other parts are left unexploited in the forest as logging residues. These parts left unused in the forest have small diameters and low commercial values, whereas those with a diameter of 1.5 to 6 cm can be used as PFR. The purpose of the thinning treatment is to provide the desired structure to the stand. During this treatment, 35 to 55% of the standing tree volume is removed. Thinning treatment can be performed until the final felling treatment starts. After extracting the industrial woody parts of the trees, the remaining thick branches can be used as leaf and chipboard wood, the raw material for pulp and paper, and fuel wood. The remaining thin parts of the branches and the woody parts at the top of the stems with a diameter of 1.5 to 6 cm can be used as PFR. The entire stand is removed during the final felling treatment. Thin parts of the branches left in the stand and the woody parts at the top of the stems can be used PFR just like in the thinning treatment.

In calculating the PFR to be obtained during both the early thinning and final felling treatments in this study, needles, conifers, shoots, and very thin branches smaller than 1.5 cm diameter of top parts were not taken into account. This was because it was aimed to keep the nutrients of these fractions in the forests in order to mitigate certain ecological risks. Furthermore, the stem barks were also excluded from the calculation. The first reason is that the cut-to-length wood harvesting method has been used, in which bark is peeled and only the marketable parts of a tree are removed. The second reason is that bark is an organic resource for the nutrition of forest soil. Furthermore, the whole tree method that requires the extraction of a whole tree is avoided, since the harvesting system using core and intermediate technologies are preferred in Turkey.

It was assumed in this study that the PFR could only be obtained from the woody biomass, which might make one suspect that the costs would be higher. However, the great abundance of labor force provided by the village people in the forests in our country (15 million man per day) and the use of cut-to-length method facilitate the availability of only the woody biomass as PFR because village people living in the forests remove the thin branches of the trees with machete and axe during the silvicultural treatments in order to obtain fire wood. Therefore, it was assumed that this treatment, which would otherwise be time-consuming and expensive, could be theoretically and technically performed thanks to the abundant work force. It was also assumed that the primary forest residues could be supplied technically since the harvesting operations were also labor intensive. However, detailed cost analysis about whether or not the PFR harvesting operations would be economical was not the subject of this study.

The spatial potential of PFR was estimated using GIS as a decision support system by integrating different kinds of spatial data in geodatabases, forest inventory data, and yield tables. Stand polygons, roads, and digital contour lines were used as the primary data layer in the GIS. The tabular data of the stand polygons was used to map stand type, forest function, site class, and slope (Fig. 2). Figure 2 shows the spatial distribution of the brutian pine forests in the study site and the topographical structure of the area. The spatial-based potential of available wood biomass was estimated *via* the GIS tools and functions in version 10.0 of ArcGIS® software (Environmental Systems Research Institute (ESRI); USA).

The study site constitutes the core area covering 80% of the standing tree volume of brutian pine in IFR. Pareto analysis was performed to select the study site by ranking the most productive sites in the entire area. PFR was derived only from the removed pure brutian pine stands that were managed by the production function and located on low-sloped areas with good site classes. Bark, shoots, and fine branches with needles were not included in the primary forest residues. Furthermore, a ton was the unit of weight used for the fresh green biomass. The dictionary of terms and units of measure compiled by Eker *et al*. (2013) was used for the terms and unit conversions. The growing stock was assumed to remain unchanged for the entire planning period because a specified forest management plan is for 10-year periods.

The volume of the forest growth (increment) in the planning period and extraordinary allowable cuts were not taken into account. Young stands that did not yield woody products (stands with individual trees younger than 7 years) were excluded from the calculation. Only planned production rates that contain periodically allowed cut volume for 10-year periods depending on forest management plan were used in this study.

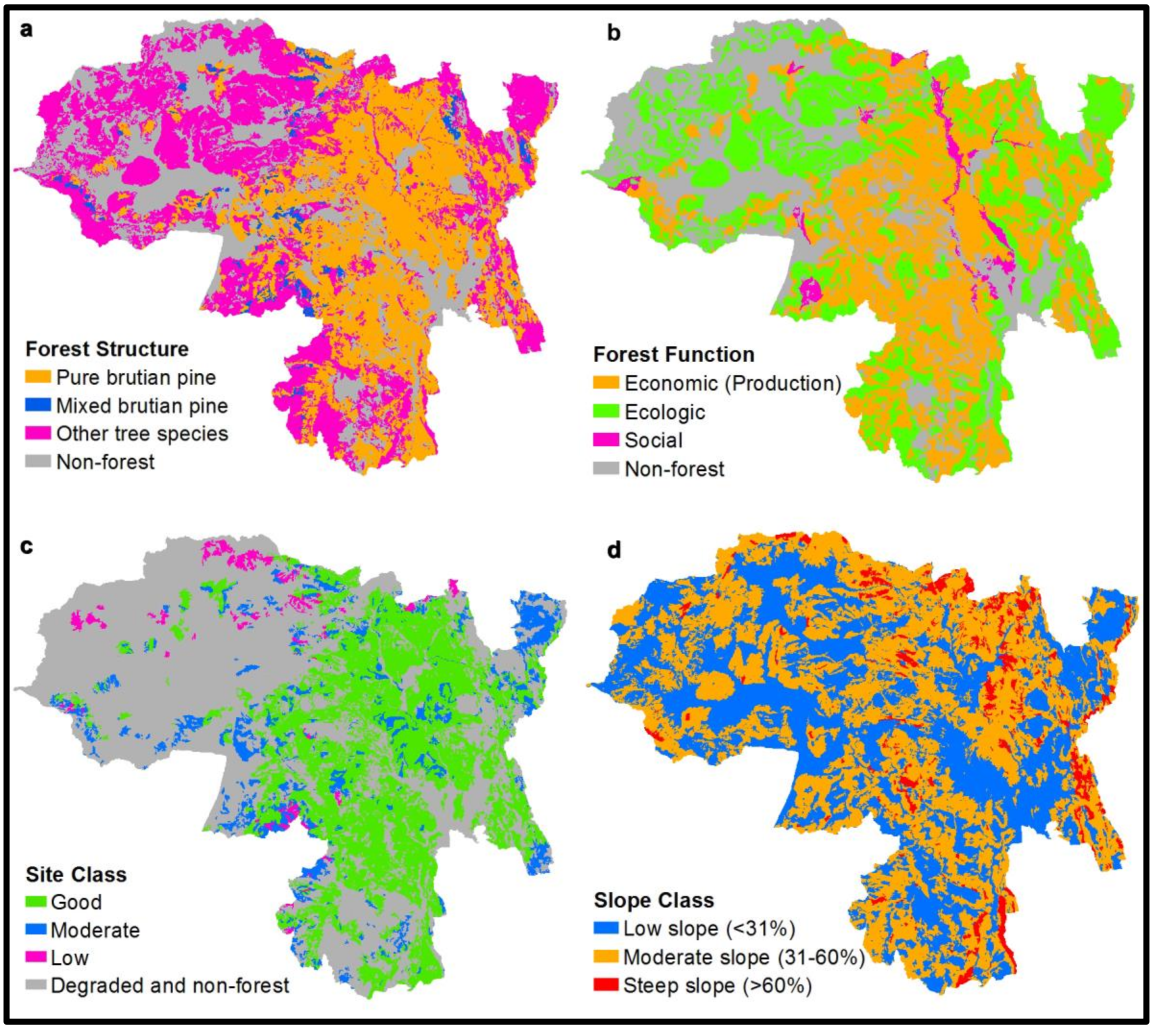

Fig. 2. Site characteristics of the study area: (a) forest structure, (b) forest function, (c) site class, and (d) slope class

EXPERIMENTAL

Methods

The periodical supply potential, availability of timber, and PFR in profitable stands were methodologically estimated using the following steps: (1) Theoretical supply potential of forest biomass within the study site was estimated using the detailed forest inventory data using the forest management plan. During this process, the quantity of the annual or periodical increment was assumed to remain constant within the planning period with respect to the age-structure and growing stock level of the forests. The quantities of PFR in all brutian pine stands were proportionally calculated to estimate theoretical (biological) potential by a hierarchical selection procedure. The quantity of PFR is a function of both the stem and branch wood utilized as traditional fuel wood. (2) After the selection process, productive stands managed by economic function that have good site classes and are located on appropriate slopes can be identified. Thus, environmental and technical limitations that reduce the total residue biomass quantity that can be extracted from forests were defined. Additionally, the theoretical potential found in the first step was integrated with the partial limitations of technical and environmental factors *via* the selection procedure. (3) The hauling distances from productive stands to a concentration center for a possible power plant place or terminal point were calculated using straight lines to estimate economic viability. The spatial supply potential was analyzed using GIS tools. (4) The resulting potential could be referred to as the theoretical and technical potential, as it contains both environmental and economic sustainability aspects. Thus, the spatially available potential of PFR was considered to be a fitting term (Fig. 3).

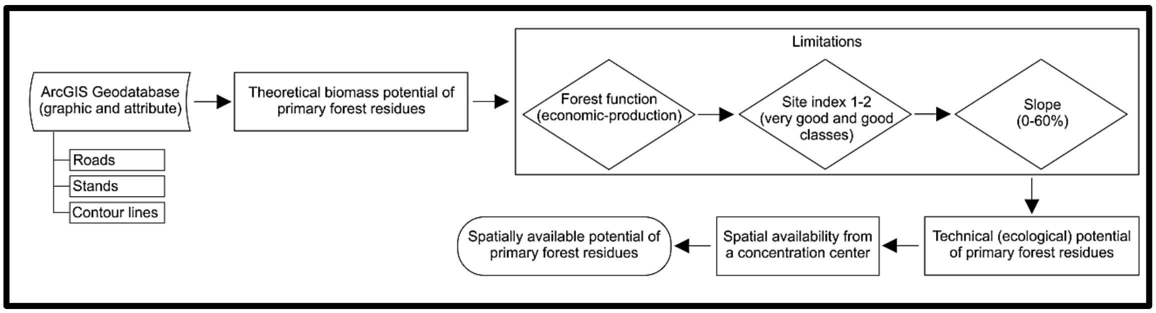

Fig. 3. Flow chart of the methodological process

Database processing

The layers of stand polygons, roads, and digital contour lines used in GIS were exported to the personal geodatabase using ArcGIS Catalog software. The attribute tables for the produced stand polygon layer consisted of data such as the feature ID, stand type, tree species, site class, slope, forest function, crown closure, and polygon area for each polygon (Çoban 2004). The geodatabase did not contain standing tree volume and an allowable amount of cut volume data. Staff of the GDF took inventory periodically to calculate such data for each stand type by tree species available in the stand. The tabular data were transferred to a Microsoft Access database.

The inventory data of the forests in the study site were integrated in Microsoft Access software, and a single inventory table was produced. The integrated inventory table was added to the geodatabase using the “import external data” command in Microsoft Access. The query design tool was used to add both the stand and inventory tables in the database to the query section. The plan ID, stand type, and compartment number were matched. "Structured query language" (SQL) was used so that the standing tree volume and allowable cut volume data could be transferred from the inventory table to the relevant sections of the stand attribute table. This new stand table was used as the forest biomass geodatabase in subsequent stages of the study.

Quantification of PFR

To calculate PFR as woody biomass, one needs to follow a sequential process focusing on stand development stages using a geodatabase query in the ArcGIS software. At the end of this process, an attempt was made to determine the theoretical potential of PFR biomass. Using this process, the allowable biomass quantity in the planning period was derived and the data infrastructure was created for primary forest residues. Table 3 shows the total area where all silvicultural treatments were performed, the standing tree volume in these areas, and the periodical allowable cut volume in these stands (for 10 years).

Table 3. Theoretical Forest Biomass Potential for Pure Brutian Pine Stands in Study Site (without any limitations)

Silvicultural treatment	Total area (ha)	Standing tree volume (m^3)	Allowable cut volume (m^3)
Early thinning	10,130.9	404,608.5	87,473.5
Thinning	29,518.2	5,617,472.3	382,052.4
Final felling	10,310.0	2,320,407.3	928,162.9
Total	49,959.1	8,342,488.1	1,397,688.8

The PFR potential of a stand was estimated using a hierarchical process that was dependent upon the descriptive statistics in stand tables designed for each stand during the forest management planning period. In this procedure, the periodical supply potential of PFR was calculated on the basis of the removable volume rate (RV_r in percentage for 10 years), fuel wood rate (FW_r in percentage), and primary forest residue rate (PFR_r in percentage). The removable volume rate was found after silvicultural treatments applied to the above-ground biomass (standing tree volume (StV, m^3)). The theoretical potential of primary forest residue essentially was estimated using the following equations (Eker 2011):

$$\mathrm{RV} = \mathrm{StV} \times \mathrm{RV}_r$$
$$\mathrm{FW}_1 = \mathrm{RV} \times \mathrm{FW}_r$$
$$\mathrm{FW}_2 = \mathrm{FW}_1 \times \mathrm{cf}_{stere}$$
$$\mathrm{FW}_3 = \mathrm{FW}_2 \times \mathrm{cf}_{ton}$$
$$\mathrm{PFR} = \mathrm{FW}_3 \times \mathrm{PFR}_r$$

In the equations, RV is the removable tree volume (m^3), which is equal to the proportion of the standing tree volume in a stand depicted in the forest inventory tables. This illustrates the periodically allowable cut volume, *i.e.*, the ratio of the extracted volume to the felled tree volume (stocks of over-barked tree volume). Therefore, as a coefficient, RV_r was assumed to be 14% of all final felling operations, ranging from 6.5% to 10% for commercial thinning operations to 35% of early thinning in pure brutian pine stands (FMP 2008). These rates (RV_r) were applied to each stand separately in varying proportions according to features of the stand's development stage (Table 4).

Table 4. Rates and Coefficients used in Calculation Procedure

Silvicultural treatment	RV_r (%)	FW_r (%)	Cf_{stere} (m^3 to stere)	Cf_{ton} (stere to ton)	PFR_r (%)
Early thinning	35	24.1-26	2	0.55	60
Thinning	6.5-10	15-20	2	0.50	50
Final felling	14	11.1	2	0.45	45

Fuel wood biomass (FW; FW_1 in m^3, FW_2 in stacked cubic meters (steres), FW_3 in green ton) was the quantity of the fuel wood in terms of felled tree volume. After calculating FW biomass, units were converted to estimate the PFR quantity. First, FW quantity was converted from m^3 to steres using the cf_{stere} coefficient (Eker 2011; Fırat 1973). Second, the quantity was multiplied by cf_{ton} coefficients to obtain the value in terms of green tons (Eker *et al*. 2013; Kalıpsız 1984). Finally, the value in green tons was multiplied by the PFR rate to estimate the PFR quantity in green tons. PFR is defined as the weight of fuel wood in green metric ton that is contained within the total removed tree biomass in a stand. Primary forest residue rate (PFR_r) is the ratio of the primary forest residue removed outside of the forest to the fuel wood biomass. This rate varies at each development stage and in different silvicultural treatments.

Estimating available potential of PFR

A gradual and interrelated calculation strategy was employed to estimate the available potential of primary forest residues in the stands. The stands where pure brutian pine trees grew were selected as the first step in the calculations. In the second step, production function, ecological recoverability and renewability, technical possibility for production, silvicultural treatments, and spatially reasonable distances for accessibility were applied as the restricting criteria (RC), explained as follows:

RC-I: Only pure brutian pine forest stands that could supply woody forest biomass are suitable to harvest primary forest residues. The mixed stands in the study site and the other tree species were excluded from the study because the brutian pine was chosen as the primary species to supply biomass.
RC-II: The forest function of a stand should be assigned to the production sub-function of the economy function. This is because commercial harvesting has been restricted to produce woody products in ecologically and socially functioning forests.
RC-III: Site class should be labeled “very good” and good” (site indexes 1 and 2) (Table 1). Removing of PFR and harvesting operations for PFR procurement in the stands with poor site indexes have a negative impact on the site characteristics. Therefore, it was assumed that only those primary forest residues in the stands with good site indexes could be used.
RC-IV: Terrain slope should be less than 60%. This is because it is technically difficult to produce wood raw material and extract PFR on very steep slopes. Furthermore, removal of the primary forest residues from the steep slopes might increase the risk of erosion. Therefore, it was assumed that the available PFR potential could be obtained through the silvicultural treatments in the stands with a slope lower than 60% that were eligible for conventional and mechanized harvesting.
RC-V: Opening-up distance from the nearest road should be shorter than 150 meters or extraction distance should be less than 150 meters.
RC-VI: Spatial distance (straight line/Euclidian) from supply stands to a possible destination point (concentration center) should be less than or equal to 30 km. This distance was the maximum linear distance to access the majority of the forests biomass in the study site.

To estimate available PFR potential, the theoretically, technically, and partially economic potentials (AEBIOM & EUBIA 2006; Biomass Energy Europe 2011; ERP 2011) were calculated using the above-mentioned restriction criteria to estimate the spatially available supply of PFR potential. The estimation method focused on the following stages:

Theoretical potential: Theoretical potential is the maximum amount of aboveground biomass that is considered to be theoretically available for utilization in energy within fundamental bio-physical limits. In the case of forest residues, the theoretical potentials are equal to the total amount that is harvested (Hoogwijk 2004). In this study, the theoretical PFR potential was also calculated by the following method. Pure brutian pine stands, where primary forest residues in the geodatabase could be derived and woody biomass could be produced, were identified and marked using GIS tools. Mixed and degraded stands, protected forests, and very young stands (where woody biomass was not yet produced) were selected and excluded from the assessment procedure (according to RC-I). Periodically allowable cut volumes (m^3 per hectares) of the polygons were multiplied by the polygon surface areas to calculate the actual biomass quantity.

Technical (and ecological) potential: Technical potential is the fraction of the theoretical potential that is available within the framework of the existing techno-structural conditions and with the current technological possibilities. Spatial confinements as well as ecological constraints are also taken into consideration (Ericsson and Nilsson 2006; Biomass Energy Europe 2010). Similarly in this study too, the following method was used to calculate the technical potential. Using GIS tools, the ecologically harvestable forest stands where pure brutian pine trees grew were identified by applying the restriction criteria (RC-II and RC-III). In this manner, the stands that might be ecologically recoverable were discovered and the primary forest residues that could be obtained from such stands were calculated. However, the terrain slope was taken into account to estimate the potential of primary forest residues in the stands that were accessible and where biomass could be produced *via* available technologies to calculate the technical potential accurately. Functional classes of terrain slope illustrating accessibility to a forest stand were used (RC-IV). A slope map was generated *via* the ArcGIS 3D analysis tool. The mean average of the slopes within the stand polygons was calculated and added to the geodatabase. The desired slope ranges were found in the geodatabase; stands within these ranges were marked, and the PFR quantity was calculated for each stand.

Spatial supply (techno-economical) potential

The spatial distribution of harvested stands was also taken into account when estimating the technical potential. Spatial distribution symbolizes the total supply cost because it is a function of both the extraction and transportation distances. A statistical analysis tool was used to create a concentration center, which was located for a possible combination heat and power plant or terminal facility. The road network layer was used to calculate the transportation distances from the production polygons to a concentration center. The transportation distance was a function of extraction and hauling distance; therefore, extraction distances were also calculated. Then, the two-sided opening-up area at distances of 100, 150, 200, and 250 meters for each road segment was calculated on the road network map *via* buffer analysis. Average skidding distance was agreed to be 150 meters (*RC-V*), as it was found that more than 80% of the standing tree volume could be opened up at a skidding distance of 150 meters.

For easy and quick calculation of hauling distance, straight lines from the centroids of the stand polygons to the concentration center, called the Euclidean distance, were measured with the GIS tool. Accordingly, the average linear hauling distance was found to be 13.4 km. For the physical distance, the road distances were measured by linear distance in 80 routes. The real distance was found to be 25.4 km on average, and the correction factor was 1.89, which was a function of the winding and wandering factor of a real road route. Accordingly, circular buffer zones with radius of 5, 10, 15, 20, 25, and 30 km (*RC-VI*) were created with respect to the concentration center. The total quantities of PFR in those zones were calculated using the GIS. The aforementioned correction factor (1.89) was used to calculate the real hauling distance of those zones based on the linear radius.

RESULTS AND DISCUSSION

Theoretical Potential of PFR

Within the study site where brutian pine forestlands in the Isparta Forest Region are primarily concentrated, the total biomass supply potential was found to be 1,397,688.8 m^3 as a function of allowable cut volume per ten-year planning period (Table 5). About 66% (928,162.9 m^3) of the total RV value was obtained from final felling, whereas 27.3% (382,052.4 m^3) and 6.3% (87,473.5 m^3) were obtained from commercial and early thinning operations, respectively.

Table 5. Theoretical PFR Potential of Pure Brutian Pine Stands in the Study Site

Silvicultural treatment	RV Allowable cut volume (m^3)	FW_1 Fuel wood potential (m^3)	FW_2 Fuel wood potential (stere)	FW_3 Fuel wood potential (ton_{green})	Theoretical PFR (ton_{green})
Early thinning	87,473.5	21,492.6	42,985.2	23,641.8	14,185.1
Thinning	382,052.4	61,288.0	122,576.0	61,288.0	30,644.0
Final felling	928,162.9	103,026.1	206,052.2	92,723.5	41,725.6
Total	1,397,688.8	185,806.7	371,613.2	177,653.3	86,554.7

The PFR quantity *per* tree primarily depended on the branch wood capacity of a tree (only the portion of a branch without leaves that could be used as fuel wood) and the silvicultural treatments applied. The total quantity of the branch wood (FW_1 in Table 5) that could be used as fuel wood was 185,806.7 m^3 *per* 10 years. About 55% of that value would be derived from final felling, 33% from thinning, and 11.6% from early thinning. On the other hand, it was also found that 13% of the total biomass in the study site consisted of fuel woods. The theoretical potential of PFR was also found to be 86,554.6 green tons for the planning period. After the theoretical PFR potential was calculated, it was found that 12.4% of the total biomass (in weight units; 1 m^3 = 500 kg) could be produced as a biologically available quantity, which is compatible with the findings of Eker *et al*. (2013).

Technical (and Ecological) Potential

Forest functions (economic, ecological, and social) influence the distribution of PFR. Therefore, 77.5% of the theoretically available PFR (67,051.5 tons) exists in wood production forests, 19.6% (16,993.9 tons) in forests with ecological functions, and 2.9% (2,509.3 tons) in forests with social functions (Fig. 4). Intensive wood harvesting operations have been carried out in the production forest. Therefore, some environmental impacts and nutrient reduction can be minimized with the supply of PFR from the forest stands with production function. The PFR quantity obtained from forests with ecological and social functions was excluded from this study for a truer estimation of available potential.

According to Figure 4, with respect to the distribution of PFR quantity by site classes, 90% (77,913.7 tons) of the forest residue was found to be in good site classes. On the other hand, based on the slope classes that restrict the technically available quantity, 26.5% of the PFR quantity (22,950.3 tons) was found in zones with a slope less than 31%. Likewise, 68.1% of the PFR quantity (58,960.8 tons) was found in zones with a slope incline ranging from 31% to 60%, and 5.4% (4,643.6 tons) was contained within zones with a slope greater than 60%.

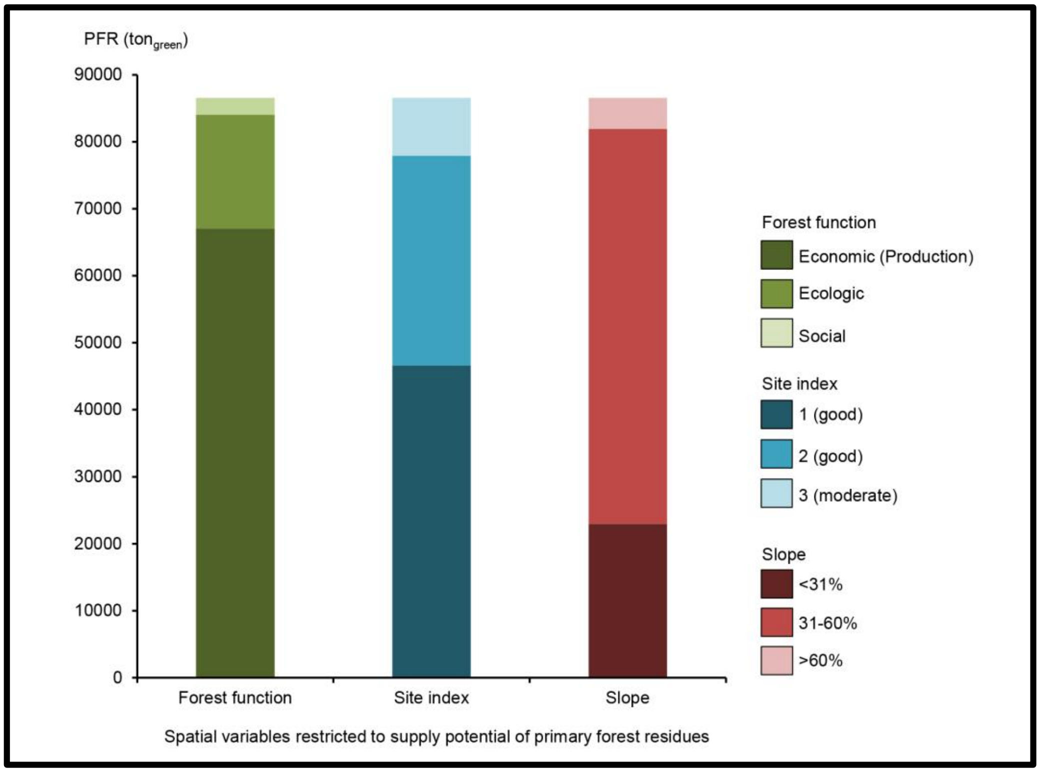

Fig. 4. Distribution of theoretical potential of primary forest residue

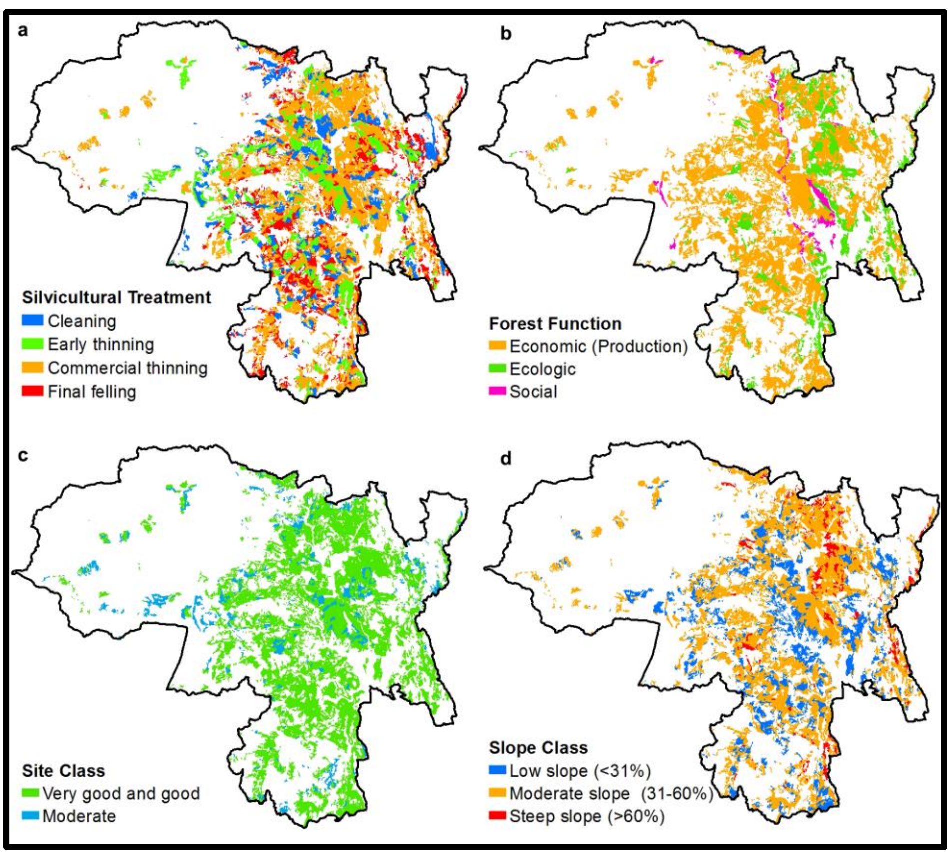

Fig. 5. Available PFR biomass potential by technical and ecological restrictions: (a) silvicultural treatment, (b) forest function, (c) site class, and (d) slope class

It is possible to access and harvest 94.6% of PFR by manual or semi-mechanized harvesting techniques in areas where slopes are lower than 61%. The PFR quantity can be derived from early thinning, commercial thinning, and final felling treatments. Therefore, 85% of the total area (59,000 hectares) of pure brutian pine stands (as seen in Table 1) was taken into account. Figure 5 indicates the spatial distribution of the available PFR by technical and ecological restrictions.

Technical potential takes into account both technical and ecological potential because the ecological restrictions are a significant factor. The residues derived only from the woody parts of trees were calculated in this study, as the other parts containing abundant soil nutrients such as needles, bark, and shoots, were left in the stands (Hacker 2005). Furthermore, removing the PFR outside of the poor stands would affect renewability negatively; therefore, the theoretical PFR potential was assumed to be available in stands only with good site classes.

Spatially Available Potential of PFR

The concentration center, defined as the tree volume weighted mean center, was derived according to the harvestable PFR quantity for the study area (Fig. 6). This center represents a possible location to establish a heat and power plant or terminal point to collect raw materials.

On the other hand, the concentration center was in the middle of the areas where the road density increased (above 20 m per hectares; this is the value of generally optimal road density), the operation rate increased (above 80%), and the distance between the roads decreased (shorter than 500 m). The results led to the conclusion that the concentration center might be physically and operationally accessible as a candidate for a power plant location.

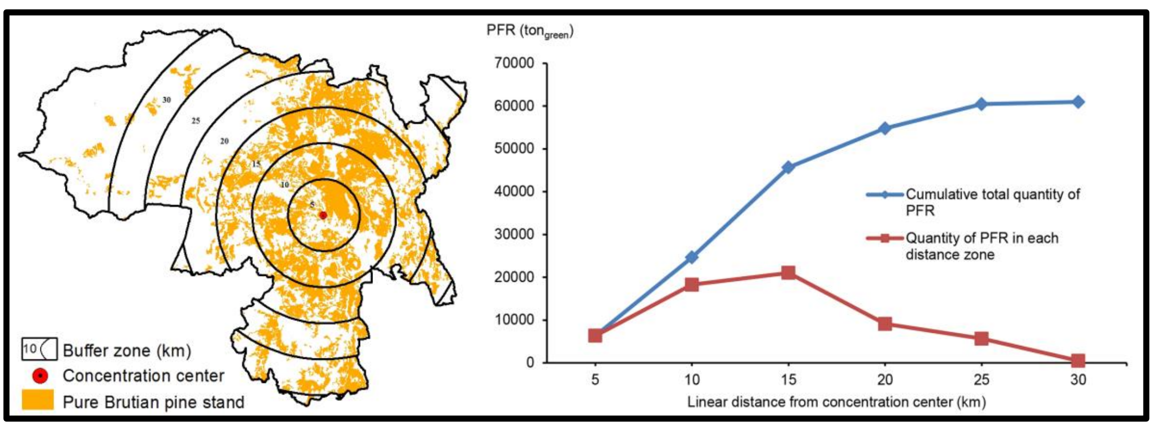

Fig. 6. Spatial supply potential of PFR biomass within the transportation zones

Depending upon the concentration center, the PFR biomass quantity available was calculated within the transportation zones at distances of 5, 10, 15, 20, 25, and 30 km (Table 6). For instance, assuming that either an allocation center or a heat-power plant was established within the concentration center, a total of 6,342.6 tons of PFR was contained within the polygons that were 5 km (horizontally) from the center within a 10-year period.

Table 6. Distribution of PFR Quantity by Distance from a Concentration Center

Distance zones (km)	Area (ha)	Volume (m^3)	PFR* (ton_{green})
5	3,503.2	567,190.1	6,342.6
10	12,286.4	2,134,584.2	24,629.6
15	24,584.5	4,153,184.6	45,678.7
20	30,115.0	5,154,717.4	54,798.9
25	33,303.2	5,714,403.4	60,458.9
30	33,857.4	5,763,726.0	60,954.5

*Technical and ecological restrictions were applied.

The results showed that 60,954.5 green tons of PFR potential were available at a horizontal distance of 30 km. Such a distance is expected to lower the transportation costs. Furthermore, many studies claimed that it would be economical to derive PFR from the production sites at distances shorter than 100 km, as a threshold value (Eker 2011; Mizaraite *et al*. 2007; Yoshioka *et al*. 2002). This limit also allowed the performance of an economic feasibility study; therefore, the partial economic potential quantity could also be calculated (Table 7).

Table 7. Distribution of PFR by Potential Types and Silvicultural Treatments

Silvicultural Treatment	Theoretical Potential	Technical & Environmental Potential	Spatially Economic Potential (0-30 km)	Available/Supply Potential (Annual)		
	ton_{green}			ton_{green}	$ton_{ovendry}$*	GJ**
Early thinning	14,185.1	11,399.6	11,362.5	1,136.2	433.57	8,688.74
Thinning	30,644.0	21,684.1	21,450.9	2,145.1	920.46	18,446.02
Final felling	41,725.6	28,279.1	28,141.1	2,814.1	1,528.62	30,633.54
Total	86,554.7	61,362.8	60,954.5	6,095.4	2,882.65	57,768.30

*Conversions from fresh green weights to oven dry weights were calculated separately for each silvicultural treatment by taking account of different moisture contents according to Eker *et al.* 2013. **Conversion to Gigajoule was performed by using the higher heating values of the PFR (Eker *et al.* 2013).

As shown in Table 7, the supply potential of the total biomass was found to be only 0.7% of the actual standing tree volume (Table 1) due to the current silvicultural treatments for sustainability. It was concluded that 71% of the theoretical potential could be supplied, despite both technical and ecological restrictions.

Hauling distances calculated *via* spatial analysis constituted a significant basis to help estimate the transportation cost in addition to the extraction cost of PFR potential (to support economic and implementation potentials). Both hauling distance and a suitable concentration center were useful to support the supply potential and feasibility despite the economic constraints.

Accordingly, spatially available PFR quantity was found to be 6,095.4 ton *per* year in this study. Approximately 70% of the theoretical potential was spatially available within the planning period, which was similar to the finding of Yamaguchi *et al*. (2013). The actual PFR quantity that could be acquired might be higher than the amount calculated in this study, considering the mixed brutian pine forest and other tree species. Furthermore, 14 to 20 million cubic meters of roundwood is annually harvested in the forests of Turkey, 4,035,400 m^3 of this quantity and 1,193,400 stere fuel woods are produced in brutian pine forests (GDF 2013). So, it can be claimed that 250,000 to 300,000 green ton PFR *per* year is theoretically available from only brutian pine forests in Turkey.

However, an in-depth analysis of the potential biomass supply is needed due to the significant role of forest biomass in future energy supply. Various resource-focused studies have been carried out in recent years to analyze the potential supply of biomass energy (Ericsson and Nilsson 2006). The methodology applied in the study has typical characteristics in several aspects, such as assessment approach, potential type, geographical scope, biomass type, specific time frame, stand development stages, and forest function.

The spatially available potential of PFR could be calculated by means of a hierarchical process developed after the elimination of the theoretical, technical, and economic potentials, through a process similar to the one used in Biomass Energy Europe (2011). One of the peculiarities of the methodology is that it presents a rapid potential estimation method for feasibility studies in supply chain management using GIS software. GIS has offered flexibility and major advantages to adjust the parameters or customize analyses associated with biomass resources dispersed in a large geographical area (Fernandes and Costa 2010; Shi *et al*. 2008; Voivontas *et al*. 2001). A great deviation in determining biomass potential can also be noted in the biomass resource assessment procedure, as researchers were externally influenced by biomass categories, biomass type, potential type, time frame, and geographical coverage (Biomass Energy Europe 2010; Böttcher *et al*. 2012; ERP 2011). In this study, a resource-focused assessment approach was implemented. Thus, essentially theoretical and technical potentials were taken into account to determine the supply potential of PFR.

CONCLUSIONS

1. Determining the theoretical potential of forest biomass is useful to assist in finding the utilization rate, but not sufficient enough to reveal the available potential. Therefore, technical, ecological, socio-economic, and implementation potentials should be calculated as well.
2. The methodology implemented in the study illustrates that it is possible to estimate available PFR potential by means of a hierarchical framework using spatial information. This allows an easier assessment of the available biomass resources in a feasibility study and a plan for its utilization as a bio-energy source. The use of GIS-based models to estimate biomass potential may offer valuable information for investors, managers, and other stakeholders. The performance of the GIS-based model should be tested in future operational inventory studies from a multidimensional perspective using multiple criteria.
3. The forest inventory data derived from the forest management plan can be used to calculate the PFR through conversion factors based on fuel wood proportion.
4. It can be concluded that the technically and ecologically available PFR potential can be estimated based on several limitation criteria, such as productive forest stands, gentle or moderate slopes, and thinning and final felling operations.

5. The GIS-based model encourages the stakeholders to make a credible decision on the selection of the allocation center for a possible heat and power plant by evaluating the biomass supply chain.

ACKNOWLEDGMENTS

We are grateful for the financial support of the TUBITAK (Scientific and Technological Research Council of Turkey), with Grant. No. 110O435.

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Article submitted: March 10, 2014; Peer review completed: April 30, 2014; Revised version received and accepted: May 12, 2014; Published: May 19, 2014.