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GIS modelling of forest wood residues potential for energy use based on forest inventory data: Methodological approach and case study application

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Abstract: This paper presents an approach to perform geo-referenced estimations of forest wood residues availability for energy use based on forest inventory data integration into a GIS. Three different estimation methods are described. The first one evaluates biomass availability based on the application of biomass expansion factors to stem volume data of the forest inventories. The method accounts for forest dynamics and assigns management treatments in function of forest properties. The second method estimates available forest wood residues applying biomass production by tree, derived from field studies, to the inventoried tree species. The third method links inventory data with national statistics of final cuttings of commercial tree species. Useful biomass potential is then estimated based on ecological, logistic and economic constraints. The methods were tested in a case study in Northern Spain where optimal facilities location based on marginal delivery costs and resources competition between facilities were found. Results are presented for three different scenarios. Biomass resources estimations under the different methods result in significant differences. GIS maps of useful biomass availability estimations are presented giving an idea of the optimal locations for bioenergy facilities based on resource availability.

Keywords: GIS; forest wood residues, biomass, Northern Spain, forest inventories.

1. INTRODUCTION

Estimations of aboveground biomass have gained importance in recent year as they are used to evaluate the carbon content in forests as a need for Greenhouse Gases Emissions Inventories in order to achieve the Kyoto Protocol target in committed countries (Brown, 2002). As present forest inventories only account for stem volume wood, total biomass estimations have to be made in order to consider the whole tree carbon content (Chhabra *et al.*, 2002). These methods are based on extrapolations of forest inventory data and are used to estimate the non-commercial available biomass, as this information is not often given at present in forest inventories and they are the potential source to supply bioenergy facilities.

Biomass-to-energy projects are highly geographically dependent (Noon and Michael, 1996). Estimations of feedstock availability allow to determine bioenergy facilities optimal location and size, and to estimate biomass supply costs from forest parcels to the power plant (Voivontas, 2001). Consequently, inventory data needs to have a geographical support in order to estimate biomass delivery costs and potential facilities location.

Even though different biomass estimation methods exists, their applications to bioenergy systems rely generally on the application of one method and constraints for resources use as feedstock for an energy facility are not always included. In this paper we present an integrated approach that combines three biomass estimation methods including limitations of the resources availability to calculate the useful biomass potential.

Depending on data availability, the structure of the forest inventory data and the purpose of the estimation, different methods can be applied. Methods based on allometric equations are not included because it was difficult to integrate individual tree data into the GIS environment. Consequently, proposed methods are based on the use of biomass expansion factors (BEF) and residues production ratios applied to inventory data at the parcel level. Estimations based on wood stem volume assume that the logs will be cut and used for other purposes while the remaining biomass (branches and leaves) will be used as feedstock for a bioenergy facility.

2. GENERAL OVERVIEW

The main characteristics of each method are presented in Table 1. The first method (M1) estimates biomass availability based on the application of biomass expansion factors to stem volume data of the forest inventories. The method accounts for forest dynamics and assigns forest management treatments (FT), such as thinnings and final cuttings, in function of forest development stage (FDS), rotation period and tree species. The second method (M2) estimates available forest wood residues applying residues production data by tree, derived from field studies for each forest treatment, to the inventoried tree species present in the forest parcel. The third method (M3) links inventory data with national statistics of final cuttings of commercial tree species by applying BEF to the commercial stem volume of exploited tree species in the parcel.

Table 1. Comparison of biomass estimation methods.

	Classification			
Method	Input data source	Input variables	Estimation	Growth
M1	NFI	VCC (T) + IAVC (T)	BEF	Dynamic
M2	NFI	VCC (T), Na	BUP	Static
M3	NFI + NFS	VCC (R)	BEF	Semi-dynamic

NFI: National Forest Inventory, NFS: National Forest Statistics, VCC (T): NFI wood stem volume in the parcel, IAVC (T): NFI wood stem volume annual increment, VCC (R): NFS wood stem volume from commercially exploited species in the parcel, Na: Number of trees, BEF. Biomass expansion factors, BUP: Biomass unitary production derived from regional field studies, Dynamic: forest annual growth is considered and FDS is projected to the life time of the energy facility, Static: Estimations are based on present FDS, Semi-Dynamic: Forest growth is indirectly considered in NFS wood stem volume.

Useful biomass potential is then estimated based on ecological, technical and economic constraints. The first ones account for soil protection and biodiversity preservation. The second ones reflect biomass losses during logistic operations, forest accessibility, and recovery rates. Finally, economic limitations consider resources competition and production costs.

3. THEORETICAL BIOMASS POTENTIAL ESTIMATION

The theoretical potential is the quantity of biomass from forest management activities (expressed in $ton.yr^{-1}$ or $MWh.yr^{-1}$) that a region can produce in a predefined period of time. This potential represents the quantity of forest wood residues (FWR) generated in a region, and can be considered as the upper bound of the bioenergy feedstock that can be obtained from forests in the area. This potential is a function of the forest type, the main tree species present in the forest, the exploited tree species, and the forest treatments applied to them.

Forest type depends on the fraction of the parcel covered by forest. This data is provided in the NFI at the parcel level (1 km^2) and classifies forests from dense to disperse woodlands. Disperse forests do not generate much residues and its collection can be costly, so biomass estimations are recommended to be done from dense forest types. Tree species differ in geographical location, rotation period, growth, forest management practices, aerial biomass, heating value and packing density. Location is given in the NFI. However, the other data has to be linked and estimated from other sources. Some forest inventories contain data on forest management practices that can also be linked. On the other hand, this information has to be validated with current practices in the study region.

Theoretical biomass potential is obtained as the sum of the biomass quantities present in each parcel for the whole region.

M1. Assigning forest management based on forest dynamics

For each FDS (regeneration, sapling, pole, and timber) an average age class is assigned based on the rotation period of each selected tree species in the parcel. Then, the plantation is projected for the next 20 years (the life time of the bioenergy facility) and FT are assigned in function of tree age. As a consequence of forest growth, FDS will change over time. First thinnings are applied to sapling parcels, commercial thinnings to pole and timber parcels and final cuttings to timber parcels. No treatment is applied to regeneration parcels and only one FT is assumed for each FDS. Each FT is applied to a certain percentage of the parcel according to current practices. Available biomass is then projected till the moment when the FT is applied by multiplying the steam volume and its annual increment by their BEFs. Specific BEFs are applied to calculate the useful fractions (all aboveground biomass, branches, and leaves). Forest residues production for each tree species by parcel is estimated as the sum of the biomass generated in each FT. The annual harvestable biomass ($ton.yr^{-1}$) at each forest location for a 20 years period is obtained (Solla-Gullón, 2006).

Table 2 shows an example for *Pinus radiata*. In this case, (rotation period: 32 years) the present regeneration surface (average age: 2.5 years) will develop until a timber stage of 22.5 years. That is to say, theoretically, this surface will undergo a first thinning at 8.5 years that will affect 40% of the surface and a commercial thinning at 16 years that will affect 37% of the surface. The resulting biomass amount in the first thinning will be the result of multiplying 0.40 by the projected steam volume at that age and by the respective BEFs. In the same way, biomass amounts would be estimated for the rest of the FDS and tree species.

Table 2. Example for *Pinus radiata*

FDS	Age Range		Mark Age	Age Evolution		Mass Status							Forest Treatment							Applied Surface					
						2.5	8.5	16	26	32	2.5	8.5	2.5	8.5	16	26	32	2.5	8.5	8.5	16	26	32	2.5	8.5
R	0	5	2.5	22.5		R	S	P					NT	FT	CT					0.4	0.37				
S	5	12	8.5	28.5			S	P	T					FT	CT	CT				0.4	0.37	0.35			
P	12	20	16	32	4			P		T					CT		FC				0.37		1		
T	20	32	26	32	14					T	R	P					FC	NT	FT				1	0	0.4

M2. Field studies data

Field studies allow validating modelled estimations with current values in the study region. These values are linked to the inventoried number of trees present in each parcel for each FDS, obtaining the biomass availability by tree species in each forest location.

The biomass obtained in each parcel i for all FT and all tree species a is calculated as: $BT_i = \sum_{a=1}^{A} \sum_{FT=1}^{T} BT_{i,aFT} \,.\, S_{aFT} \,.\, N_a$, where, $BT_{i,aFT}$ is the biomass quantity generated per tree, per FT and per tree species in parcel ($ton.tree^{-1}$), S_{aFT} is the surface of the parcel where the FT is applied (%) and N_a is the number of stands of that species in the parcel. In order to consider forest dynamics Na should be projected for the life time of the energy facility.

M3. Final cuttings of selected tree species

Final cuttings produce most of the wood residues generated by a forest plantation during its rotation period (Kallio and Leinonen, 2005). Moreover, these residues represents the most economically and technically biomass fraction to be used in a bioenergy system. As biomass availability is dependent on forest commercial exploitation, available amounts of forest residues are subject to final cuttings of commercial wood. Scenarios derived from this methodology are assumed to be the most realistic as they take into account the real quantity of biomass that is produced annually in the region. On the contrary, only biomass from final cuttings can be estimated as it is difficult to obtain statistics of biomass volumes generated in other FT from exploited species.

The biomass estimation method is based on the link between geo-referenced inventory data and national statistics of commercial cuttings. The average volume of commercial wood (VFC) annually cut from each tree species in each province is obtained and assigned to the forest parcels depending on FDS. For short rotation period species all FDS are considered, as it is assumed what those parcels are the ones to be exploited in the next 20 years. For medium rotation period species pole and timber stages are considered and for long rotation period species only the timber stage is considered. VFC for each tree species and province is divided by the number of forest parcels containing the selected FDS, and assigned to the geo-referenced points where those combinations (species-FDS) are present. Then, BEFs are applied to convert VFC of each parcel and tree species into annual biomass quantities (d.m. ton.yr^{-1}). No biomass increments are considered as VFC already represents the real annual wood volume available in each forest location.

4. USEFUL BIOMASS POTENTIAL

Useful biomass potential is defined as the biomass quantity (tons.yr^{-1} or MWh.yr^{-1}) that can be used for energy after applying constraints. These limitations accounts for protected areas, land ownership, terrain slops (accessibility), soil protection, recovery rates, biomass use competition, and operational costs.

Environmental sustainability is accounted for by leaving aside protected areas from the available forest resources and by leaving a fraction of forest residues in the parcel for soil protection. Public and private forest management may introduce limitations for biomass extraction. Some parcels may not be accessible or operational due to terrain slope. Different production methods and related costs are linked to terrain slopes. Moreover, not all harvested biomass can be collected. Recovery rates of logging residues depend on the logging method, the harvesting season and if the residues are harvested fresh or dried. Competition for the biomass resource should be assessed in the region for the life time of the energy facility, considering feedstock for other uses and for other energy facilities. The availability reduction will depend on biomass price and geo-political decisions. Operation costs accounts for the biomass collection, haulage and packing. Considering the collected biomass fraction, the terrain slope and the forest management strategy different production costs are obtained

The constraints can be applied by GIS overprint of layer or by calculations at each parcel of the NFI.

5. CASE STUDY

5.1. Description

In the framework of the BIOFOREST project- Waste wood to energy in Northern Spain-, energy facilities were planned to be installed in the Basque Country and its neighbour provinces. The covered area is 41’201 km^2 from which 15’024 km^2 (36%) are dense-wooded forests. The purpose was to recover 84 d.m. kton.y^{-1} of forest wood residues from commercial forest management to produce torrefied wood and supply a 22 MWe gasification unit. The objective of the study was to define the optimal location for bioenergy facilities based on biomass availability and delivery costs. The overall approach

and costs data are detailed in Panichelli and Gnansounou (2007). For this paper, we focus on the estimation of the biomass useful potential.
Three scenarios were modelled and biomass potential was estimated using the three methods described. Scenario E1 estimates final cuttings' biomass of short rotation species, scenario E2 assess final cuttings' biomass of exploited species with technological improvements (bailing system with chipping at power plant) and E3 estimates first and commercial thinnings and final cuttings biomass of short and long rotation period species. No biomass estimations for E3 under method M3 were made, due to lack of data.

5.2. Database development

The software used was the ArcGIS® version 9.1. Supporting software such as Microsoft Access® and Microsoft Excel® was also included for data processing and modelling. The source data was the CAD format National Cartographic Database 1:200'000 produced by the National Geographic Institute. This database is available for each province under study. Forest accessibility was assessed based on the Digital Terrain Model with a 1:200'000 resolution from which terrain slopes were calculated.

Forest inventories were obtained from the Biodiversity Database of the Spanish Environmental Ministry. The decision to work with the most present data has lead to use different forest inventories. However, due to their different structure it was not possible to create a geo-referenced database relating tree species with diametric classes and forest location for the whole region. For these reasons, the BEF method was applied to calculate total harvestable biomass. Data from the Third National Forestry Inventory (NFI3, 2006) was available for the regions of Navarra, La Rioja and Cantabria. For the other regions (Bizkaia, Alava, Gipuzkoa and Burgos) the Second National Forestry Inventory (NFI2, 1996) was used. Forest inventories have a 1: 50'000 resolution. In the first case geo-referenced information by forest parcel (points representing 1 km^2) includes the three more relevant species, with their respective forest type and ownership. A set of tables is also provided containing location of the sample points, number of trees, stem volume (under and over bark), stem volume annual growth, and complementary data. The NFI3 provides a large amount of information. But, georeferenced data is limited and covers the same variables as in the NFI2. Data is presented by parcel and by FDS.

Main tree species for the studied region have been selected in function of overbark stem volume (VCC) production ($m3.province^{-1}$). National forest statistics from the National Institute of Statistics between 1996 and 2003 were processed and an annual average value was obtained. Tree species VCC productions were increasingly ranged and summed up to reach 80% of the VCC production of the province (representing the main forest exploited species). Twelve tree species were selected from which biomass availability was estimated. Depending on the FDS of the tree species different biomass fractions have been considered.

A geo-referenced database integrating both NFI was created with the forest parcels that are wood dense forests and contain at least one of the twelve selected species.

5.3. M1. Theoretical forest management.

It was assumed that only one forest treatment is applied in each FDS. Selected treatments were: first thinning, commercial thinning, and final cuttings. Pruning was not included. Forest management data for each tree species was taken from the `Repoblación y Manejo Forestal´ Manual of the Gipuzkoa Government.

5.4. M2. Field studies data.

Field studies have been carried on in the Navarra region by the CENER in the framework of the Bio-South project (Techno-economical assessment of the production and use of biofuels for heating and cooling applications in South Europe). Biomass generated by forest treatment and by tree species was used to make estimations of the biomass theoretical availability under each scenario.

5.5. M3. Final cutting of commercial tree species.

Stem volume final cuttings' statistics were used to define biomass availability based on actual forest exploitation. The information was presented by province and by tree species. Statistics were taken from the Annual Spanish Statistics. For *Eucaliptus globulus* and *Populus nigra* all FDS were considered. For *Pinus radiata* pole and timber stages were taken into account. Only timber stage was considered for *Quercus* spp, *Fagus silvática* and other *Pinus* with long and medium rotation period.

5.6. Useful potential

Protected areas in the region (wetlands, National Parks and Biosphere Reserves) have been left aside from the availability of FWR. No constraints were found for land ownership and parcels with terrain slopes above 20% were considered but assigned a higher operational cost. 30% of total harvestable biomass at each parcel was left aside for soil protection. Recovery rates were assigned in function of the efficiency of forest residues production activities. Estimations were based on data for large scale production of wood chips from forest residues (Elsayed *et al.*, 2003). Total recovery rates considering soil protection and process efficiency are 61% for fresh residues and 46% for dried residues. No other bioenergy facility using forest residues exists in the area. Board industry and fire wood consumption compete for the forest residues in the region. For scenarios E1 and E2 competitors demand was assumed to be covered by the forest residues provided by the other FT. For scenario E3, 30% of the recovered biomass was left aside to supply competitors based on statistics of biomass destination (NFS) of coniferous and deciduous trees at provincial level. Results at the parcel level were aggregated at the municipal level for visualization purposes.

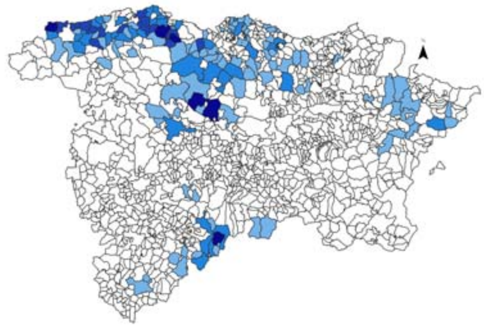
5.7. Results

Methods M1 and M2 have resulted in similar theoretical biomass estimations for scenarios E1 and E2. For E3, a significant difference exists due to biased input data for long rotation period species. Method M3 shows the theoretical potential, based on actual forest exploitation and represents the real biomass availability from final cuttings. At present, approximately one third of the theoretical final cuttings are done, giving a biomass potential of 75 - 100 d.m. ton.yr^{-1} of dried and fresh FWR, respectively, based on actual forest exploitation. For scenario E1useful potential of the studied region is 231 - 314 d.m. ton.yr^{-1} and 174-236 d.m. ton.yr^{-1} of fresh and dried FWR, respectively (Fig. 1).

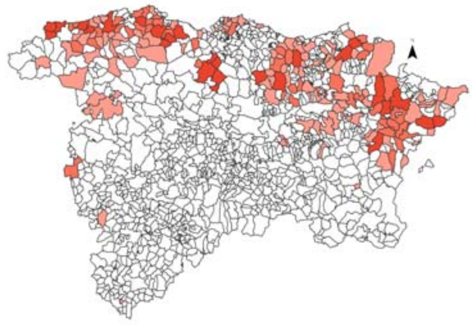
Geographical distribution of biomass resources for energy use is presented in figures 2a-f. Results show that the north-east part of the region presents the higher potential for siting an energy facility. This is due to the availability of short rotation period species that produce larger quantities of biomass during the life time of the plant.

5.8. Discussion

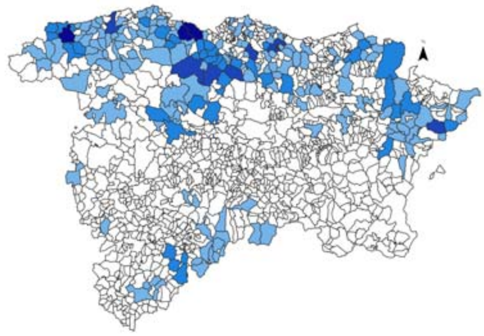
Biased results were obtained from each estimation method. Uncertainty in method M1 is linked to the use of national BEF that may not correspond to the regional values. However, more specific information was not available, and so, the BEF used to perform the National Greenhouse Gases Inventory were used. Forest dynamics was considered based on forest annual increment, as a practical way to account for forest development based on available data. Using a specific forest dynamic model may lead to more accurate estimations, but may also need specific skills and more detailed data, not always available. While M2 allows validating estimations based on regional data, field studies are costly and time consuming. For this case study, the number of samples was too low. This was a source of uncertainty as stands volume significantly vary in a forest. Moreover, projecting the number of trees in a parcel seems more difficult than projecting stem volumes, to account for forest dynamics. For this case study, estimations were done based on the present number of forest stands, and this has lead to introduce uncertainty in the estimation.



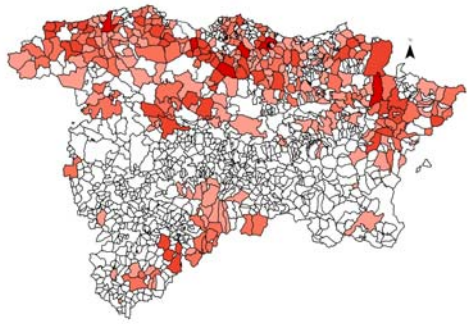
a) E2 M1dried FWR (dm ton.yr^{-1})



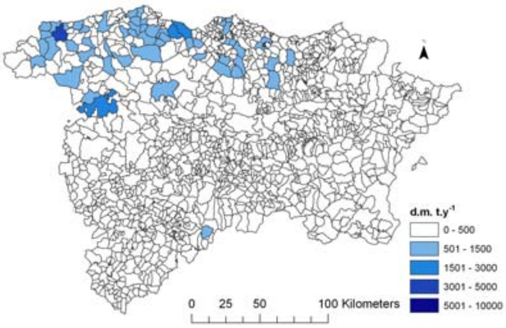
d) E1 M2 fresh FWR (MWh.yr^{-1})



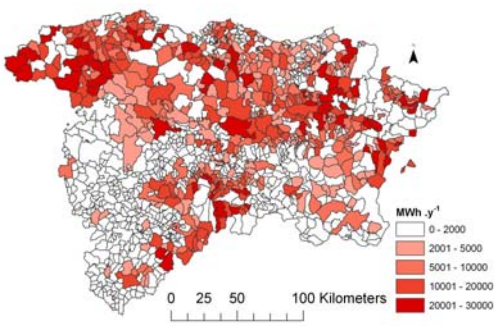
b) E2 M2 dried FWR (dm ton.yr^{-1})



e) E2 M2 fresh FWR (MWh.yr^{-1})



c) E2 M3 dried FWR (dm ton.yr^{-1})



f) E3 M2 fresh FWR (MWh.yr^{-1})

Figure 2. Geographical distribution of biomass resources for energy use. Figures a-c: Estimations for E2 under different methods for dried FWR. Figures d-f) Estimation under M2 for different scenarios for fresh FWR.

Estimations of forest residues for energy use are available from the Spanish Renewable Energy Plan (MITYC, 2005) for the whole region and for the province of Navarra (CENER, 2005). Even though the theoretical potential value is within our values, results are difficult to compare as different species and assumptions were considered. Significant biomass reductions are obtained when applying constraints, limiting the resources availability. These limitations are not considered in previous studies.

Method M3 allows to indirectly accounting for forest development, projecting statistic values of commercial final cuttings for the life time of the energy facility. For this case study, an average value of historical data was used as final cuttings' values by province and tree species do not significantly vary over time. Moreover, the estimations reflect the present forest exploitation as commercial statistics are used. On the other hand, geographical representation of forest resources is less accurate as estimations are not based on the stem volumes present in each parcel, but by distributing final cutting volumes of selected species between the forest parcels in the province with suitable FDS. This will be a source of uncertainty when estimating operational costs. The same limitation as for method M1 applies concerning the use of BEFs from other region.

6. CONCLUSIONS

Biomass estimations under the different methods have conducted to significant different results in estimating biomass useful potential, giving evidence of the influence of the selected method on forest wood residues estimations for energy use. The use of commercial statistics that reflect the real forest management, the application of constraints on biomass use and the accounting of forest dynamics are essential to perform accurate estimations. These factors may significantly reduce the theoretical biomass potential. More efforts should be done to link forest inventory data with GIS, to develop regional BEF and forest dynamic models, to generate accurate data for FT others than final cuttings, in order to decrease uncertainty of the final results. While for policy and management strategies methods based on forest inventories stem volume are recommended, for practical and commercial applications methods based on commercial forest exploitation should be preferred.

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