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Spatially explicit assessment of roundwood and logging residues availability and costs for the EU 28

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Abstract

Competition for woody biomass between material and energy uses is expected to further increase in the future, due to the limited availability of forest resources and increasing demand of wood for material and bioenergy. Currently, methodological approaches for modeling wood production and delivery costs from forest to industrial gates are missing. This study combines forest engineering, geographically explicit information, environmental constraints, and economics in a bottom up approach to assess cost-supply curves. The estimates are based on a multitude of wood supply systems that were assigned according to geographically explicit forestry characteristics. For each harvesting and transportation system, efficiencies were modeled according to harvesting sites and main delivery hubs. The cost supply curves for roundwood and logging residues as estimates for current time and for the future (2030) show that there are large regional differences in the potential to increase extraction in the EU28. In most EU Member States, the costs of logging residues extraction increase exponentially already for low levels of mobilization, while extraction of roundwood can be increased to a larger extent within reasonable costs (30-40 $/m^3$). The large differences between countries in their harvest potential highlight the importance of spatially explicit analyses.

Keywords: spatial availability, cost supply curves, woody biomass, supply systems

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Introduction

The future mobilization of woody biomass for material and energy use in the European Union is expected to increase significantly, due to growing demand for bioenergy and increasing production of semi-finished wood products (EFSOS II 2011, Mantau et al. 2010). The realistic potential of woody biomass from the European forests was estimated to be 747 million m^3 per year in 2010, and it is expected to remain almost constant until 2030 (Mantau et al. 2010). Mantau et al. (2010) expected the demand to increase from ca. 800 million m^3 to ca. 1300 million m^3 (years 2010 to 2030), by far exceeding the amount of biomass available from the forest management. The increase in harvest of wood from forests was suggested to be especially driven by demand for wood for energy, while the market share of material use demand was expected to drop from 55.5% to 43.5%. Similar development was projected also in the European Forest Sector Outlook Study (EFSOS II, 2011), where the reference scenario expected wood demand for energy alone to increase from 434 million m^3 roundwood equivalent in 2010 to 585 million m^3 in 2030. Therefore, additional wood mobilization or large increases in import of biomass are needed to secure adequate resources.

A number of studies have assessed the future potential woody biomass in the EU for material (Mantau et al. 2010, Verkerk et al. 2011) and for energy uses (Asikainen et al. 2008, Lauri et al. 2014, Daioglou et al. 2015). These studies considered spatially explicit biophysical features and land uses change for estimating the theoretical potentials and applied a series of ecological, technical and social constraints for assessing realistic potentials. However, there is a fundamental difference between available resources and the amount which can be delivered to the end user at a cost inferior to the market price – that is, resources that are economically viable.

The available amount of biomass in a certain geographical area can be associated with its delivery costs by means of cost supply curves, which show the increase of costs when enlarging the supply (Binkley and Dykstra 1987). These curves reflect the resource accessibility mechanisms, where the resources available at the lowest cost are firstly mobilized and afterwards when the demand increases, remote resources are mobilized at higher costs. Cost supply curves are useful for investigating relations between prices at the industry gate and amount mobilized, and also for benchmarking the supply of different resources. These curves can be considered to hold in the short run, while in a longer term, variations in the forest growth, infrastructures, location of industrial facilities, and afforestation/deforestation events may change the slope of the cost-supply curves.

Several studies have shown potentials and costs of forest resources by applying the cost supply curves approach in specific regions or entire countries (Galik et al. 2009, Hock et al. 2012, Yemshanov 2014, Lundmark et al. 2015) and in some cases also in regions such as the EU and on the global level (de Wit & Faaij 2010, Sikkema et al. 2014). However, as pointed out in assessments of future potentials for woody biomass in the EU (Verkerk et al. 2011, Lauri et al. 2014), there is still need for more detailed analyses of the cost-supply relationship, especially such that takes into account the spatial location of end-use facilities with detailed information of transportation networks, capitals, fuels and labor costs (Nordfjell et al. 2004, Siry et al. 2006). In this study we present a new bottom-up approach for assessing and comparing potentials and costs for roundwood and logging residues for the EU28 under different biomass mobilization alternatives and economic development options. The results are shown for current time (2015) and for year 2030. This is to our knowledge the first study that combines detailed spatial information on forest characteristics, location of facilities, and road network to produce detailed cost-supply curves for each of the 28 EU Member States.

Material and Methods

The methodological approach consisted of the following parts:

- Computation of woody biomass potentials by use of the Global Forest Model (G4M)
- Modeling of forest operations and road transportation efficiencies
- Modeling of transportation distances from forests to industries in a network analysis
- Adaptation of costs to the country borders
- Aggregation of results in cost supply curves for each of the European Regions (Table 1)

Table 1. >>>

Available biomass potential

The assessment of available woody biomass potential for current time (2015) and 2030 was based on a spatially explicit information acquired from the global forest model (G4M).

G4M is a computer model simulating land use change and forest management decisions as well as corresponding dynamics of land cover, forest biomass, harvested wood and CO_2 emissions on 0.5×0.5 degree grid (Kindermann et al. 2008, Gusti, 2010, Gusti & Kindermann, 2011). The model uses empirical forest growth functions for major tree species in each grid cell (Kindermann et al., 2013). Forest management in G4M is aimed at sustainable harvest of exogenous wood demand on country scale.

For each cell, the characteristics of forests are described through a full range of features covering important aspects such as: country, dominant tree species (Picea sp., Abies sp., Pinus sp., Betula sp., Fagus sp., Quercus sp., and Larix sp.), age structure, mean annual increment, rotation time, treatment (final felling, thinning), tree parameters (dbh=diameter at breast height, height), harvested woody biomass (solid m^3/ha/year), harvestable surface (hectare/year), the model mimics an even-aged forest management [1].

[1] Harvesting of forest areas which are strictly protected according to WDPA (2004) was excluded and no conversion or use of protected forest was allowed. Forests that are not protected are considered as potential production forest. The G4M model allocates harvests to this area so that the demand for wood for material and energy purposes will be satisfied. Forests that are used in a certain period to meet the wood demand (so–called used forests) are modelled to be managed for woody biomass production. This implies

For each cell, G4M generates the harvestable volume of woody biomass divided between two categories:

- Roundwood: stemwood with dimensional characteristics suitable for production of sawnlogs or pulplogs, with top diameters fixed according to specific dimensional requirements in each country.
- Logging residues: harvesting losses (i.e. rotten wood, wood dimensionally unsuitable for roundwood logs), tree branches, and tree tops. Tree branches and tops are calculated with specific biomass expansion factors (Teobaldelli et al. 2009) applied to the stemwood volume.

The forest attributes obtained from G4M were merged with a database of biophysical variables (Skalsky et al. 2008), containing data on soil, topography, climate, land cover with resolution from 5 to 30 arc minutes.
Homogeneous response units were delineated and clustered as five altitude classes, seven slope classes and five soil classes. The clustered units are intersected with a 0.5° grid and country borders in order to delineate homogenous Simulation Units (SimU).

The current and future harvested volumes (from used forests) in G4M are defined by assuming the fulfillment of the forest biomass demand predicted in the economic model GLOBIOM (Global Biosphere Management Model) (Havlík et al. 2011). Hence, the wood demand from GLOBIOM represents the "maximum potential" harvestable in each alternative considered in our analyses[2].

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a rotation time, thinning events and final harvest. Unused forest do currently not contribute to wood supply (due to economic reasons) and the model allows for conversion from used forests to unused, and unused to used forests. The historical geographical location of harvest within each EU Country has been initialized using a map of wood production from Verkerk et al. (2015), which was applied for sorting the economical harvest suitability of cell in the G4M.

[2] The GLOBIOM is a global partial equilibrium model of the forest and agricultural sectors, where economic optimization is based on the spatial equilibrium modeling approach (Havlík et al. 2011). The demand is based on the interaction of four different drivers: population growth, income per capita growth, bioenergy growth, response to prices. Demand increases linearly with population in each of the 57 GLOBIOM regions (including the 28 EU countries). GDP per capita changes determine demand variation depending on income elasticity values. For the agricultural sector, the income elasticities area calibrated to mimic anticipated FAO projections of diets (Alexandratos and Bruinsma 2012). Income elasticities for the forest sector are taken from Buongiorno et al. (2003). The response of non-energy related uses to commodity prices is endogenously computed in GLOBIOM. Bioenergy demand projections are implemented based on PRIMES projections for forest biomass (EU 2013). Price elasticities for the agricultural commodities are taken from a global database from USDA (Muhammad, et al. 2011) and for the forest sector from Buongiorno et al. (2003). Hence, demand for non-energy (material) wood use are competing for the wood resource with energy uses and are projected endogenously by GLOBIOM. An increase in biomass production prescribed by the output of the PRIMES biomass model is entirely reproduced in GLOBIOM.

The residues were considered to be technically harvestable in early thinnings and in final fellings. Early thinnings were simulated for forest stands with average stem volume < 150 – 250 dm^3, with the threshold adjusted according to country.

Ecological restrictions were applied on forest soils sensible to erosion and loss of fertility. For soil erosion, residue extraction in forest areas that have slopes with an inclination >50% was not allowed for broadleaved forests and limited to 33% of conifer sites. On slopes with inclination between > 30 and ≤50%, the extraction was limited to 33% of broadleaved and 66% of conifer stands. Forest soils that have low levels of soil carbon content are sensible to losses of site fertility (Repo et al. 2014). For this reason, removal of logging residues was totally excluded from areas where the level of carbon in the topsoil was below 0.6%, determined in EC (2006). Poorly developed soils can also be negatively affected by the extraction of residues, thus soils with depth less than 30 cm (EC 2006) were also excluded.

Technical losses were modeled according to site specific harvesting and extraction systems. In case of highly mechanized systems (harvester/forwarder based), the losses were assumed to 30% of total available amount (Nurmi 2007; Wihersaari 2005). For systems based on motor-manual felling and processing, losses were assumed to 40% (Asikainen at al. 2008).

Modeling of supply costs

The cost of supply of woody biomass from each SimU (in $/solid m^3) to the industry gate included the cost for logging operations and costs for road transportation to the gate. In the case of roundwood from final felling, also the cost for forest regeneration was included. The efficiency of each operation was modeled according to the characteristics of each SimU, and afterwards combined with the unitary costs for operating capitals, labor and fuels adapted to the economic conditions in each of the countries in the EU.

Regeneration costs

Due to the lack of information on the spatial distribution of areas regenerated by human activities within country border, each SimU in final felling was divided according to the regeneration shares in its EU Region (FE 2011): one part regenerated by planting and one naturally regenerated.

The time consumption for regeneration activities was set to 26.8 hours/ha, herein planting was set to17 working hours/ha according to Granhus & Fjeld (2008), the pre-commercial thinning time consumption to 6.2 hours/ha according to Ligne' et al. (2005), the rest of the time was assumed to be spent in complementary work (eg. soil preparation).

The hourly cost for regeneration was assessed in Sweden according to forest accounting statistics as 43 $/hour (Brunberg 2014). The adaptation of this cost component to the country borders followed the same adaptation used for the "labor costs" for forest operations (see paragraph "*country specific adaptation of unitary costs*"), due to the fact that the man-power is the largest component in the semi-mechanized regeneration methods. The cost per hectare for regeneration activities was allocated on the volume of roundwood harvested in final felling from each SimU.

Harvesting and primary transportation systems

The forest harvesting systems applied in the EU can be divided into low mechanized and highly mechanized systems, based on the man-power required (Table 2). In the low mechanized (System 3-10 in Table 2), tree felling is carried out motor-manually by means of chainsaws, while in the mechanized ones (System 1-2 in Table 2), harvesters are typically used. Another division of systems can be made on the basis of locations where trees are processed into logs. In the cut-to-length (CTL) systems (System1-6), the processing takes place at the forest site (at the stump), while in the whole tree system (WT), trees are processed at the roadside/landings (System 7-10). The extraction of trees/logs can be made with specialized machinery: forwarders, skidders, cable yarders, or by means of farm tractors equipped with forest trailers. In the case of extracting whole trees (WT), roadside processing of trees into assortments needs to be included in the supply chain. This operation can be made with processors mounted on excavators or motor-manually using chainsaws.

The selection of harvesting systems to be assigned to each SimU was based on the restrictions listed in Table 3. The size of trees was used as limiting factor for felling with harvesters, the slope as a limiting factor for highly mechanized felling and extraction and the soil bearing capacity as a limiting factor for extraction with heavy machinery (forwarders).

Typically, roundwood harvesting systems in the EU are based on CTL, and WT systems are applied in case of integrating roundwood and residues on steep terrains (i.e. slope above 30%). Thus, in the modeling of forest operations, the CTL systems were assumed as reference for calculation of costs in the case of exclusive removal of roundwood, while WT systems were applied to units where roundwood was integrated with residues on slopes above 30%.

In the case of collecting residues in CTL systems, the cost of piling residues during felling is included, and also the time consumption for extraction of residues to the roadside. In case of WT systems, the cost of piling residues at roadside with a processor/chainsaw is included as a cost. In all cases (both CTL and WT), chipping at the roadside by means of truck-mounted chippers is included as a cost in the supply chain of residues (Table 2).

To account for areas where unfrozen peatlands prevent the use of heavy machinery (forwarders), a map of soil freezing areas (freezing at least for one month at 20 cm depth) was created for the EU, based on WorldClim (2015) and Beltrami (2001). The soil freezing map was merged with the peatland dominated SimUs for selecting areas where forwarders where assumed not being able to be used.

A decisional support framework was used for selecting of harvesting systems applied in each SimU (Figure 1). Firstly, it considers whether logging residues are extracted, for selecting between CTL and WT systems. Secondly, technical restrictions for each machinery (Table 3) are considered. Skidders are applied only in a SimU unsuitable for forwarders/farm tractors and cable yarders are assigned to units unsuitable for the rest of machineries. Finally, the selection between high mechanized forest systems (harvester, forwarder, and processor) and low mechanized (chainsaw, farm tractor) is obtained by applying the system with the lowest cost per unit of product (Figure 1).

Figure 1 >>>

Table 2 >>>

Table 3 >>>

Two truck and trailers systems were included in the supply model. One is based on typical trucks and a trailer used for transportation of logs (pulp logs and sawlogs) for transportation of roundwood. The other one considered was a container truck for transportation of chipped logging residues.

Modeling of harvesting and transportation efficiencies

A series of time consumption models for forest machinery and road transportation were collected from the literature. Each model provides the time consumption per harvested unit (solid m^3), given a set of spatial explicit variables for each SimU. The biophysical variables included were terrain and forest features. The variables included in each time consumption model are used for adaptation of time consumption to the SimU according to Annex 1.

Technical and economic utilization factors, based on follow up studies, were collected for each machinery/equipment and applied for conversion of effective time consumption (effective minutes/m^3) (Annex 1) into gross time consumption (scheduled machine hours/m^3) and for assessing the economic life of different machinery/equipment (Annex 2).

Both work efficiencies and technical and economic utilization factors were assumed to be little influenced by the demographic borders, assuming an average operator and average magnitude for the forest companies, irrespective of country border.

Country border adaptation of time-unit costs

The time-unit cost in forest operations according to Ackerman et al. (2014) can be divided in three main components: fixed, operational, and labor costs.

The fixed costs are composed of capital costs, represented by depreciation and interests on the invested capitals.Other fixed costs are annual costs for insurances, taxes, registrations, and garaging of equipment.

Operational costs include fuels, lubricants, maintenance and repair, running gears, and other consumables. These costs are solely incurred when the machine engine is running, therefore can be calculated as a costs per SMH (cf. Ackerman et al. 2014).

The fuel cost can be calculated by multiplying the fuel price by the fuel consumption per hour. The lubricant cost is commonly estimated as percentage on fuel costs.

The cost for maintenance and repairs is based on the annual cost records incurred in workshops, or in case it is not directly available, it is estimated as a percentage on purchase price.

The labor cost includes wages directly paid to operators for their work and indirect costs, such as social charges and other benefits (daily allowances, insurance, transport, etc.). Wages are usually paid per scheduled work hours (SMH).

On the top of the direct costs, also overheads are incurred when owning and operating production assets, representing general administration costs for a company. These costs are difficult to allocate to specific production items, therefore an average value can be assumed.

Time-unit costs for machinery and labor are country specific, thus needing an adaptation across borders. For that scope, hourly costs (per SMH) for each machinery system were collected from databases in Reference countries and divided between the most relevant cost components according to Annex 3. The costs are collected in local currencies (LCU). The fixed and operational costs are converted into international U.S. dollars ($) using official exchange rates[3], and labor costs are converted to comparable units using Purchasing Power Parity conversion factors (PPPs)[4]. A global benchmarking exercise was initiated in September 2014 with a group of experts from 15 countries, as listed in Annex 4. A detailed description of hourly cost for a machinery felling trees was collected from the experts with a standardized procedure according to Ackerman et al. (2014). The exercise explored the needing for adaptation to the country borders for each of the time-unit cost components and parameters.

The results from the benchmarking exercise evidenced the need for adaptation to the country border of the following time-unit cost components: *Purchase price, Interest rate, Insurance, Fuel price, Maintenance and repair cost, Labor cost.*

[3] The official exchange rates were collected from the World Bank & International Monetary Fund (IMF) (http://data.worldbank.org; www.imf.org). The exchange rates are affected by short time fluctuations. As we thrive to reflect the long term exchange situation, we selected a 5 years average exchange rate (2009-2013) (see Annex 5).

[4] The PPP conversion factor expresses the number of units of a country's currency required to buy the same amounts of goods and services in the domestic market as U.S. dollar would buy in the United States. The PPP conversion factor was obtained from The World Bank International Comparison Program database (http://data.worldbank.org), the average of last 5 available years was used (2009-2013), the PPP conversion factor is available for 199 countries (see Annex 5).

Forest production assets are mostly traded on international markets. Therefore, the country border adaptation for purchase prices for machinery/equipment (*Pc*) was found to be dependent on the level of protection on local markets represented by trade tariffs[5] (*Tf*) and the profitability of forest markets expressed by the value added per employee from roundwood production (VAE)[6] (Annex 5).

The following regression is proposed in the adaptation of purchase price of machinery to a Country "j" border:

$$Purchase\ price\ (\$)_{j} = Rpc \times \left(\frac{(380\,533 + 909 \times VAE)}{1 - Tf/100}\right) \qquad \text{(Eq. 3)}$$

The adaptation was based on the purchase price of an harvester, for other machineries the factor *Rpc* (ratio to harvester purchase price) is needed for correcting their price level compared to an harvester (see Annex 3).

Interest rates were found to be correlated to the risk for investment in the different countries, represented by the *international country risk index (ICRG*[7]*)*, and the following country border adaptation is proposed:

$$Interest\ rate\ (\%)\ j = 81.8707 - 17.4439 \times \ln(ICRG) \qquad \text{(Eq. 4)}$$

Insurances were found to be dependent on purchase prices, therefore their adaptation to the country borders was indirectly obtained by the adaptation of purchase prices.

The adaptation of fuel prices from the reference country "*Ref*" to the Country "*j*" border is obtained by use of the "net official fuel sale prices"[8] (Annex 5) as:

$$\text{Fuel Price}_{j}\ (\$/l) = Fuel\ Price_{ref} \times \frac{Net\ official\ fuel\ Price\ j}{Net\ official\ fuel\ Price\ ref} \qquad \text{(Eq. 5)}$$

Maintenance and repair costs are commonly assessed as percentage on the purchase prices, therefore, as for the insurances, their adaptation is obtained by the adaptation of purchase prices to country borders.

In forestry, labor force is locally available, and its cost is expected to be connected to the cost of living in the different countries. The labor cost is formed of wages and social charges, and these two components

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[5]The international trade tariffs for manufactured products are available from The World Bank (http://data.worldbank.org/). The average value for period 2009-2013 was used: the data was available for 172 countries and measured as a percentage on the price of traded commodity. (Annex 5).

[6] Gross value added per capita from roundwood production (*VAE*) ($ per capita): the value added per capita was calculated by dividing the Gross Valued Added from roundwood production ($) by the number of employees in roundwood production. Both data were retrieved from FAO (FAO 2014) and were available for the year 2011 for 175 countries. (Annex 5).

[7] The International Country Risk Guide (ICRG) (https://www.prsgroup.com) is a 5-year composite index forecast that expresses the overall concern for investing in a specific country, providing a combined rating for political, financial and economic risk factors for each country. This forecast was available for 139 countries. The index assumes values between 0 and 100, where higher values represent lower risk. (Annex 5).

[8]A global collection of gasoline and diesel prices was retrieved from GIZ (2013). The most recent update for GIZ was released for 165 countries (year 2012). Value added taxes (VAT) are commonly excluded from the computation of costs incurred by forest companies, therefore VATs were collected from The World Bank Group database (http://www.doingbusiness.org) and subtracted from the diesel price from GIZ, obtaining a net official fuel price (Annex 5).

are treated separately. Wages were correlated to the PPP ratios[9] (Annex 5) and adapted by using the relation between PPP ratios in different countries as:

Wage $_j$ (\$/SMH) = $Wage_{ref} \times \frac{PPP\ ratio\ j}{PPP\ ratio\ ref}$ (Eq. 6)

Country specific social charges are added to the wages according to the country border labor cost/wage ratio[10] (Annex 5).

The total cost for harvesting system in a generic country (j) is determined according to Eq. 7.

Total Harvesting Cost $= \sum_{1}^{i} \frac{Tc_i \times Cj}{60 \times U_i}$ + *Oh*; (*i=operation; j=country*) (USD/m^3) (Eq. 7)

tc_i= time consumption in the operation (i), given by the Annex 1.

Cj= country border adapted hourly cost for operation (i), given by the cost parameters in Annex 3 and the specific adaptations by Eq. 3-6.

U_i= Utilization rate of machinery used in operation (i), given in Annex 2.

Oh= overhead costs; overheads are incurred when owning and operating production assets, they represent general administration costs for forest companies. In the benchmarking exercise, their level varied between 5-15% of direct costs, depending on the size of forest enterprises, therefore a 7% on operational costs is assumed for an average condition.

In Systems including cable yarding (CYL, CYW), the total costs is also increased by 2.38 \$/m^3 for installation of cable lines and this cost is adapted to the country border according to labor costs (i.e. Austria as Reference Country).

Modeling of transportation distances

The open street map (OSM 2015) was used as information layer for road network analyses. The industrial facilities in each country were assumed to be located in the largest cities according to population sizes, as a proxy for real locations of current industries. The number of cities chosen for each country was assigned to match the number of industrial facilities in that country. First, we took the average between the number of pulpmills (Annex 6-7) and woody biomass power plants (>0.2 MW). Then we chose a corresponding number of cities, in the order of their population count and starting from the largest. Sawmills were excluded from the analysis, due to the unpredictability of their business life. A database of current industries (RISI) was used as reference for current number of pulp and paper mills, and the Platts (2013) for the woody biomass power plants (including co-firing industries).

[9]The PPP level ratio, also referred to as the national price level (price level ratio of PPP conversion factor to market exchange rate), makes it possible to compare the cost of the bundle of goods that make up the gross domestic product (GDP) across countries. It tells how many dollars are needed to buy a dollar's worth of goods in the country as compared to the United States. The price level ratio of PPP was obtained from the World Bank International Comparison Program database (http://data.worldbank.org), the average of last 5 available years (2009-2013) was available for 182 countries (Annex 5).

[10] Social charges on wages were obtained from The World Bank Group database (http://www.doingbusiness.org), the information was available for 174 countries and applied to the country borders (Annex 5).

Modeling of transportation costs

A methodology similar to the one used for forest machinery was applied for adaptation of transportation costs to and across the country borders (see Annex 8).

Sensitivity analyses

The sensitivity analysis focuses on assessing the impacts of changes on transportation costs, economic conditions, and woody biomass demand.

In the *Standardized Transport* alternative, the effect on supply curves of transportation distances to industries was evaluated by considering a fixed transportation distance of 50 km for all harvested units (SimUs).

The cost-supply curves for2030 were calculated for two alternatives named *Economic Growth* and *Forestry Intensification,* in order to gain insights on how changes in crucial parameters influence the shape and form of the cost-supply curves.

In the *Economic Growth* alternative, the price of diesel and GDP per capita in each country were assumed to develop according to the forecast for 2030 made according to the "EU Reference Scenario" (EU 2013). The growth of wages in the reference countries was estimated by applying a deflator of 0.85 to the growth of GDP per capita, based on the long term relation found by Chien & Arias (2015). The PPP ratios in this case were obtained by comparing the differences in expected growth of GDP in the different countries. The expected variation of GDP per capita, PPP ratios and diesel prices applied in this new scenario are listed in Annex 11. The maximum potential of harvestable woody biomass (i.e. used forests) is assumed the same as in the *Reference.*

In the *Forestry Intensification* alternative, the used forest area expands due to higher share of future demand for bioenergy allocated to forests. This is based on assumption of scarce development of dedicated bioenergy crops compared to the *Reference* (miscanthus, switchgrass and short rotation coppice reach 3.1 M ha compared to 7.1 M ha). In the *Forestry Intensification*, the growth of GDP and fuel prices are expected to be the same as in the *Economic Growth* and the bioenergy demand to be the same as in the "EU Reference Scenario" (EU 2013).

Results

EU Region level

The results are clustered according to geographical regions within the EU (Figure 2-3-4). The total harvested volume of roundwood in the "Reference scenario" is estimated to be 584 Mm^3. Of this total potential 39% is expected from Central-West countries, 34% from the North of EU, 16% from Central-East, 8% from South-West and 3% from South-East.

The current amounts mobilized correspond generally to a cost level of ca. 26-34 \$/m^3 (Figure 2). In the whole EU, it would be possible to mobilize 56% (329 Mm^3) of the total projected harvest at a cost below 30 \$/m^3. When increasing the cost to 40 \$/m^3, the mobilized roundwood amount reached 482 Mm^3 (82% of potential). North and Central-West EU has capacity to increased their amount respectively of 27-44 - Mm^3 and 98-108 Mm^3, before reaching a cost of 40-45 \$/m^3, where the supply curves became exponential. Central East EU, South-East and South-West are already close to the steep part of their curves and they can increase the mobilized volume of respectively 26-30 Mm^3, 7-8 Mm^3, 14-17 Mm^3, before entering the exponential growth of cost-volume ratio at 40-45 \$/m^3 (Table 4 and Figure 2).

The total potential volume of logging residues in the "Reference scenario" is estimated to be 79 Mm^3, corresponding to 13.5% of the roundwood potential volume. Of the total volume of logging residues, 45% is expected from the North of EU, 31% from Central-West, 10% from Central-East, 10% from South-West and 3% from South-East. The cost supply curves for residues are generally linear in the cost range between 25 and 40 $/m^3$ and became exponential after that threshold. In the whole EU, at a cost below 30 $/m^3$, it would be possible to mobilize 10.1 Mm^3 (13% of potential). If increasing the cost to 40 $/m^3$, the mobilized volume reaches 53.3 Mm^3 (67 % of potential).

If we consider a cost limit of 40-45 $/m^3$, the largest amounts are expected form North and Central West EU, reaching 22-28 and 18-20 Mm^3 respectively. If considering the same cost threshold, the amount mobilized in Central-East, South-East and South-West are expected to be respectively 6.9-8.1-, 1.7-1.9, 5.4-6.3 Mm^3 respectively.

Table 4 >>>

Figure 2 >>>

EU Country level

Roundwood

Almost 60% of the total roundwood is produced in four countries, namely France, Sweden, Germany and Finland (Figure 3).

The lowest supply cost per SimU (intercept of cost supply curves) is observed in Poland, Czech Republic and Germany. Considering a maximum delivery cost of 20 $/m^3$, the largest amount of delivered biomass was observed in Germany. If increasing the maximum delivery cost to 30 $/m^3$, the largest deliveries were observed in Germany and Sweden, significant amounts were also delivered in France, Poland, Finland, and Czech Republic. Considering a maximum cost of 40 $/m^3$, the largest deliveries were expected in Germany, Sweden, France and Finland (Table 5).

Table 5 >>>

Figure 3 >>>

Logging residues

The countries with the largest potential were: Sweden, Finland, France and Germany. Countries with relevant contributions are also Spain and Poland (Figure 4).

The lowest supply costs per SimU (intercept of cost supply curve) were observed in Croatia, Czech Republic and Austria. For a maximum cost of 20 $/m^3$, the volume of logging residues delivered to the industry would not be significant in any of the EU countries. If increasing the cost to 30 $/m^3$, the largest delivery were observed in Germany, relatively high amounts are also delivered in Czech Republic and Austria. If considering a maximum cost of 40 \$/m^3, the largest delivery were expected from Sweden, Finland and Germany (Table 6).**Table 6** >>>

Figure 4 >>>

Roadside costs

If excluding the road transportation costs from the cost supply curves, it was observed that the production costs at the roadside were generally between 10 and 30 \$/m^3 for roundwood, and between 15 and 30 \$/m^3 for logging residues. At a cost below 15 \$/m^3 it was possible to mobilize the largest volume of roundwood from Central-West and by Central-East EU. At roadside costs below 20 \$/m^3 the Central-West and North of EU assumed a leading role (Figure 5).

At a cost below 25 \$/m^3 it was possible to mobilize the largest volumes of logging residues from Central-West and Central-East EU. At a cost below 30 \$/m^3 the North of EU and Central-West became the regions with the largest supply (Figure 5).

Figure 5 >>>

Sensitivity analysis

In the *Standardized Transportation* alternative, if setting a limit of 30 \$/m^3, it would be possible to mobilize 399 Mm^3 of roundwood (68% of potential) in the EU. This is 12% more than in the Reference case. Thus, a downward shift of the curves is observed, meaning that generally the average transportation distances for roundwood in the Reference case were longer than 50 km. The largest gain in cost competitiveness is observed for North of EU, especially if compared to Central-West due to higher load capacities in road transportation and relatively lower density of facilities assumed in the Reference case (Table 7). A significant gain in competitiveness is also observed for Central-East compared to Central-West (Figure 6).

In the *Standardized Transportation,* at a cost below 40 \$/m^3, it would be possible to mobilize 73.3 Mm^3 of logging residues (93% of potential), which is 38% more than in the Reference. Also for logging residues, the standardization of transportation distances increased competiveness for North of EU and Central-East compared to the Central-West (Table 7 & Figure 6).

In the *Economic Growth*, if setting a limit of 30 \$/m^3, it would be possible to mobilize 291 Mm^3 of roundwood (50% of potential) in the EU, which is 6% less than in the *Reference*. With a cost increase to 40-45 \$/m^3, the mobilized volume reached 461-501 Mm^3 (79-86 % of potential), which is a 3-6% less than in the *Reference* conditions. The increases in cost levels did not change the cost competitiveness between the regions. The main effect of the new cost levels was generally an upwards shift of the whole curves making less wood available as compared to the *Reference* (Table 7). The average increase of the intercepts for the curves in the whole EU was 0.5 \$/m^3 (3.0 %), when compared to the *Reference* (Figure 7 & Annex 12).

In the *Economic Growth*, it would be possible to mobilize 6.8 Mm^3 (9% of potential) of residues at cost below 30 \$/m^3, and for a cost below 40-45 \$/m^3 it is expected that a volume of 48-61 Mm^3 (60-78% of potential) would be mobilized, thus a 2-7% reduction of supply can be expected compared to the *Reference* scenario. As noticed for roundwood, also for logging residues the curves are generally shifted upwards. The average increase of the intercepts in the EU was 1.1 $/m^3 (5.2%) compared to the *Reference* curves (Figure 7 & Annex 12).

The total volume of roundwood in the *Forestry Intensification* alternative is estimated to be 685 Mm^3, a 17% increase of total EU potential compared to the *Reference* scenario. Of this total potential, 37% is expected from Central-West countries, 31% from the North of EU, 19% from Central-East, 10% from South-West and 3% from South-East. Thus, the greatest increase of available volumes is expected from Central-East EU. In the whole EU, at a cost below 30 $/m^3, it would be possible to mobilize 301 Mm^3 (44% of potential), that is 28 Mm^3 less than in the *Reference* curves. If increasing the cost limit to 40-45 $/m^3, the mobilized roundwood volume reaches 517-569 Mm^3 (76-83% of potential). The greatest difference in volumes available at the different costs is expected in Central-East EU, where 15-35 and 37 Mm^3 more than in the *Reference* curves are available at a cost of 30-40 and 45 $/m^3 (Table 7). The intercepts of the cost supply curves for roundwood are similar to those in the *Economic Growth* (Figure 7 & Annex 12).

The total potential volume of logging residues in the *Forestry Intensification* alternative is estimated to be 91 Mm^3, which is 15.6% larger than in the *Reference* scenario. Of this total volume, 42% is expected from the North of EU, 30% from Central-West, 13% from Central-East, 12% from South-West and 3% from South-East. The greatest increases of available volumes are expected from North and Central-East EU, where respectively 5.7 and 3.1 Mm^3 more than in the *Reference* case will be available. In the whole EU, at a cost threshold of 30 $/m^3, it would be possible to mobilize 8 Mm^3 (9% of potential), that is 2 M m^3 less than in the Reference curves. If increasing the cost to 40-45 $/m^3, the mobilized volume reached 55-70 Mm^3 (61-77 % of potential). As noticed for roundwood, the greatest difference in volumes available at the different costs is expected in Central-East EU (Table 7). In this condition, the number of countries where logging residues can be delivered at a cost lower than 20 $/m^3 increased from 10 to 14 compared to the *Reference* case. However, for a maximum cost of 20 $/m^3, only marginal volumes of logging residues are delivered to the industry (Figure 7 & Annex 12).

Figure 6 >>>

Figure 7 >>>

Table 7 >>>

Discussion

The results of our analyses show that there is potential to increase roundwood harvests and logging residue extraction in the EU28, but only in a few countries. In most European countries, the costs of logging residues extraction increase exponentially already on low levels of extraction, while roundwood can be harvested to a much larger extent with reasonable costs. The potential for increasing biomass mobilization varies largely between different countries, highlighting the importance of spatially explicit analyses and decisions. Our findings support the existing literature on the topic, and add on it by showing the cost-supply relation of roundwood harvests and logging residues extraction with an unprecedented spatial detail.

At costs below 30 $/m^3$, a large share of roundwood (44-68% of potential) but only a small share of logging residues (9-13%) can be mobilized. In all countries, the mobilization of logging residues was found to be much more sensitive to changes in costs than mobilization of roundwood.

The economic potential of forest biomass harvest varied largely between the countries. At low supply costs (lower than 20 $/m^3$), countries in East EU (Czech Republic and Poland) together with Germany would be able to mobilize the greatest share of roundwood because of respectively the low harvesting costs and the high density of industries. If higher costs are considered, Central Europe (Germany and France) and the Nordic Countries (Sweden and Finland), are able to mobilize large volumes at reasonable costs due to the large potentials of woody biomass per unit of land, high density of industries combined with efficient transportation. In other regions, costs increase strongly already with low levels of harvests, indicating a low economic potential for increased harvests. Similar results are seen also for extraction of logging residues, in this case the Nordic Countries (Sweden and Finland) assume a leading role, although relevant supply will not be possible at a cost lower than 20 $/m^3$.

If willing to achieve larger volumes, countries in Central-East and South EU will require important infrastructural investments, in order to be cost competitive with Central-West Europe (Germany and France) (Figure 2). An economic growth in the European Union will reduce the roundwood volumes mobilized at the different costs by 3-6% and the availability of residues will be reduced by 2-7%. An intensification of forestry, by increasing the forests managed for production will considerably increase the amount of mobilized biomass at the different costs in the EU. This is especially prominent in countries in the East EU (Czech Republic, Poland).

The differences in cost levels between different countries are generally in line with the findings of Asikainen et al. (2008), who also showed that the Czech Republic and Poland are highly cost competitive for supply of logging residues in the EU. However, based on previous literature we were expecting that also other countries in the East EU and in the Baltics could deliver significant amounts of biomass at low cost levels (de Wit & Faaij, 2010). This was not reflected in our findings. A possible explanation is that in our approach we adapted the interest rates for invested capitals to the risks incurred across country borders, which lead to higher capital costs for mechanized systems used in less stable economies. In the long term, it could be expected that the risk in the whole EU will converge, leading to higher competitiveness of countries with emerging economies. However, the combined index that we used for measuring risk for investments gives a forecast of only five years, and it will be difficult to speculate on risk development in a longer term. Another possible reason for the high cost incurred in Baltic States and East Europe is the low density of receiving industries, thus the development of industrial sector in these areas could lead to lower costs than in our calculations, as it is shown by the standardization of transportation distance and by the supply costs at the roadside.

The potentials of logging residues for the Nordic Countries in our study are in line with the technical achievable potentials presented recently by Routa et al. (2012), and Asikainen et al. (2008). Our study showed that it will be possible to mobilize residues at costs less than 20 $/m^3$ only from forest units where whole tree harvesting systems are applied in Austria, Croatia, Czech Republic. However, these forests are located on slopes above 30%, where the supply costs for roundwood usually exceed 40 $/m^3$. For this reason, it would be relevant to combine the supply curves for roundwood with the one for residues.

We used the purchasing power parity (PPP) ratio approach for adapting the cost of labor to the country borders. As a consequence in our study, a long term convergence for labor costs to a common level is assumed. A similar possible development for labor costs was also shown by de Wit & Faaij (2010).

In this study, we did not consider social aspects connected to mobilization. In Verkerk et al. (2011), this aspect was also included, by assuming that the size of forest properties can influence the resource accessibility in the different countries. If including also this component, we can expect a reduction of supply compared to the presented results, as forest holdings in Europe are generally relatively small.

The selection of harvesting systems assigned to the forest units was based on a comparison of cost convenience between mechanized and labor intensive systems. However, also other criteria than economic ones can be used. One possible option would be to include also environmental criteria (c.f. Kühmaier & Stampfer 2010, Dimou & Malivisti 2014) and to consider also the evolution in the uses of current harvesting systems and implementation of new ones (Visser & Stampfer 2015, Visser & Berkett 2015).

In our approach, we used the largest cities in each of the countries as a proxy for calculation of transportation to the industries. While this matches reality to a certain degree, this assumption is also likely to lead to deviations in results compared to real locations of forest industries. However, the location of densely populated cities is expected to hold for longer time than the position of industries. In order to show the possible effect of higher density of wood industries (e.g. sawmills), the supply costs at the roadside and the costs at a standardized distance (50 km) were also included in this study.

Short run production costs were included in the model but also the costs for maintenance of existing forest infrastructures need to be included into a comprehensive analysis. However a specific mapping of density of infrastructural networks in relation to forests impacted by human activities can be obtained from deforestation maps (Hansen et al. 2013). Extraction distances (from stumps to roadside) are currently fixed in the calculation of efficiencies. This factor has a significant effect, and is relevant especially in hilly or mountainous areas (Spinelli et al. 2015). In our study, an initial adaptation for the EU was carried out using altitude classes.

In addition, in some of the countries, multimodal transportation by integration of trucks, trains and boat is expected to increase in the future. This could create some deviation from our results, however in the EU road transportation is still the most common mode of transport for woody biomass (Wolfsmayr & Rauch, 2014). If considering the costs in the long run, also creation of new infrastructure must be included in the model.

Stumpage fees and compensation paid to the forest owner could be other relevant components of cost paid at the industry (c.f. Lundmark et al. 2015). However, in the present study we showed only costs which can be modeled in a geographically explicit way. As the stumpage price is connected to the concept of resource scarcity and difficult to model without a comprehensive framework where also demand and supply are included, this approach is considered as an important improvement for the future.

Our findings suggest that considerable increases in logging residue extraction will not be economically feasible within the EU without intensification of actively managed forests. Instead, use of roundwood and, as suggested by Lauri et al. 2014, by-products of the roundwood-processing industry will probably be more cost-efficient for satisfying the increasing forest biomass demand than expanding the extraction of logging residues within EU28. This is an important and timely message for the political decision-makers, considering the intensive discussions about the role of forest biomass in bioeconomies, both a national and regional levels (Böttcher et al. 2012, Frank et al. 2016). It is also noteworthy that without considerable infrastructural investments in the Central East and South of the EU, most of the future supply for roundwood and residues will be possibly provided at reasonable costs mostly from Central and North EU.

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Table 1. EU 28 forestry Regions defined according to Forest Europe (2011).

Region	**Countries**
North Europe	Denmark, Estonia, Finland, Latvia, Lithuania, Sweden
Central-East Europe	Czech Republic, Hungary, Poland, Romania, Slovakia
Central-West Europe	Austria, Belgium, France, Germany, Ireland, Luxemburg, Netherlands, United Kingdom
South-East Europe	Bulgaria, Croatia, Cyprus, Greece, Slovenia
South-West Europe	Italy, Portugal, Spain

Table 2: Selected forest harvesting and road transportation systems for roundwood and logging residues.

	Roundwood (WD)					Logging Residues (LR)				
System Number	Harvesting method	Felling	Extraction	Landing	Wood transportation	Piling	Extraction	Piling at roadside	Chipping	Transportation
1	CTL	HA	FO	---	TR WD	HA_{LR}	FO_{LR}	---	CH	TRWC
2	CTL	HA	FT	---	TR WD	HA_{LR}	FT_{LR}	---	CH	TR WC
3	CTL	MFP	FO	---	TR WD	MFP_{LR}	FO_{LR}	---	CH	TR WC
4	CTL	MFP	FT	---	TR WD	MFP_{LR}	FT_{LR}	---	CH	TR WC

5	CTL	MFP	SKL	---	TR WD	----	---	---	---	---
6	CTL	MFP	CYL	---	TR WD	---	---	---	---	---
7	WT	MF	SKW	PCH	TR WD	---	---	PCH_{LR}	CH	TR WC
8	WT	MF	SKW	PCM	TR WD	---	---	PCM_{LR}	CH	TR WC
9	WT	MF	CYW	PCH	TR WD	---	---	PCH_{LR}	CH	TR WC
10	WT	MF	CYW	PCM	TR WD	---	---	PCM_{LR}	CH	TR WC

CTL= cut to length, WT=whole tree. If System 4, 5, 6 is applied >No extraction of logging residues is considered. HA= felling and processing with single grip harvester, HALR= piling logging residues with single grip harvester, MFP= motor-manual felling with chainsaw, MFPLR= motor-manual piling logging residues, MF= motor-manual felling and processing with chainsaw, FO= forwarding roundwood to roadside with a forwarder, FOLR= forwarding logging residues with a forwarder, FT= extraction to roadside of roundwood with a farm tractor, FTLR= extraction to roadside of logging residues with a farm tractor, SKL= skidding logs with a skidder, SKW= skidding whole trees with a skidder, CYL= cable yarding roundwood logs, CYW= cable yarding whole trees, PCH= Mechanized processing at the roadside (crosscutting and delimbing) with excavator mounted processor head, PCM= motor-manual processing at the roadside (cross-cutting and delimbing) with chainsaw, PCH_{LR} = piling residues at the roadside with processor, PCM_{LR} = piling residues at the roadside in motor-manual processing, CH= Chipping logging residues, TR WD = transportation of roundwood with a truck and trailer unit, TR WC = transportation of chipped logging residues with a container truck and trailer unit.

Table 3. Technical restrictions applied in the selection of forest equipment/machinery.

Operation	Tree diameter (DBH, cm)	Slope (%)	Soil bearing capacity
HA	0-50c/40b	0-30	-
MF	No restriction	0-100	-
MFP	No restriction	0-100	-
FO	-	0-30	Not applicable on unfrozen peatland
FT	-	0-30	No restriction
SKL	-	0-50	No restriction
SKW	-	0-50	No restriction
CYL	-	0-100	No restriction
CYW	-	0-100	No restriction
PCH	0-70c/60b	-	-
PCM	No restriction	-	-

c=conifers; b=broadleaves

Table 4. Mobilized amounts of roundwood and logging residues in the 5 European Regions according to current production and in case of three different cost thresholds.

	Mobilized amount (Mm^3)					
	North	Central		South		Total
		East	West	East	West	
Roundwood						
Current[1]	134.0	59.6	98.6	7.1	11.5	310.8
Cost 35 $/m^3$	136.4	80.3	175.8	11.8	19.4	423.7
Cost 40 $/m^3$	160.8	86.0	195.9	13.7	25.1	481.5
Cost 45 $/m^3$	178.4	90.0	206.6	14.6	28.7	518.3
Δ 35-40 $/m^3$	24.4	5.7	20.1	1.9	5.7	57.8
Δ 40-45 $/m^3$	17.6	4.0	10.7	0.9	3.6	36.8
Residues						
Cost 35 $/m^3$	9.4	5.0	12.2	1.1	3.9	31.6
Cost 40 $/m^3$	21.7	6.9	17.6	1.7	5.4	53.3
Cost 45 $/m^3$	28.4	8.1	20.3	1.9	6.3	65.0
Δ 35-40 $/m^3$	12.3	1.9	5.4	0.6	1.5	21.7
Δ 40-45 $/m^3$	6.7	1.2	2.7	0.2	0.9	11.7

[1]Current amount mobilized according to FAOSTAT (2013)

Table 5. Descriptive statistics of the cost supply curve for roundwood.

	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	15.34	2.3	8.1	12.7	20.0
Belgium	18.14	0.3	4.9	5.8	5.8
Bulgaria	14.98	1.3	3.7	5.3	6.3
Croatia	15.27	1.4	3.4	5.2	6.2
Cyprus	24.74	0.0	0.0	0.0	0.0
Czech	13.45	12.8	20.0	20.2	20.3
Denmark	17.22	0.9	2.7	3.1	3.1
Estonia	16.89	0.6	5.3	9.6	10.7
Finland	20.00	0.0	32.1	54.5	75.3
France	18.05	0.2	38.3	78.4	98.4
Germany	14.49	33.8	79.9	84.2	84.9
Greece	26.88	0.0	0.1	0.3	1.6
Hungary	15.44	1.3	5.1	7.4	7.9
Ireland	16.74	0.2	1.1	2.2	3.4
Italy	19.98	0.1	4.2	7.0	14.1
Latvia	21.78	0.0	4.7	9.5	12.4
Lithuania	15.96	0.8	4.4	6.3	6.9
Netherlands	15.81	0.8	1.0	1.0	1.1
Poland	12.71	11.2	34.3	40.1	40.3
Portugal	19.62	0.1	6.7	10.5	12.3
Romania	17.32	0.9	5.8	12.3	16.6
Slovakia	17.55	0.6	3.5	6.1	7.7
Slovenia	16.21	0.4	2.6	2.8	3.0
Spain	23.38	0.0	1.7	7.7	22.5
Sweden	18.51	1.2	47.5	78.7	89.4
UK	16.37	2.0	8.9	11.5	14.2

Table 6. Descriptive statistics of the cost supply curve for logging residues.

	Intercept ($/m³)	Volume (Mm³) mobilized at 20 $/m³	Volume (Mm³) mobilized at 30 $/m³	Volume (Mm³) mobilized at 40 $/m³	Total Potential (Mm³)
Austria	18.30	0.0	1.0	1.8	2.0
Belgium	26.20	0.0	0.0	0.5	0.5
Bulgaria	20.40	0.0	0.3	0.8	0.9
Croatia	16.70	0.0	0.2	0.5	0.9
Cyprus	18.70	0.0	0.0	0.0	0.0
Czech	17.20	0.0	1.2	2.1	2.1
Denmark	27.00	0.0	0.2	0.4	0.4
Estonia	25.60	0.0	0.1	1.2	2.0
Finland	29.00	0.0	0.3	9.0	13.6
France	18.40	0.0	0.3	5.5	10.9
Germany	19.20	0.0	2.5	7.7	8.1
Greece	19.20	0.0	0.0	0.1	0.2
Hungary	22.80	0.0	0.4	1.2	1.4
Ireland	23.60	0.0	0.0	0.2	0.5
Italy	18.80	0.0	0.6	1.8	1.8
Latvia	29.30	0.0	0.1	0.6	1.8
Lithuania	23.80	0.0	0.3	0.9	1.5
Netherlands	28.00	0.0	0.1	0.1	0.1
Poland	19.40	0.0	0.7	2.5	3.4
Portugal	18.40	0.0	0.3	1.4	1.8
Romania	20.40	0.0	0.1	0.7	1.3
Slovakia	22.80	0.0	0.1	0.4	0.7
Slovenia	22.70	0.0	0.1	0.3	0.3
Spain	20.10	0.0	0.7	2.3	4.1
Sweden	28.90	0.0	0.0	9.7	15.8
UK	21.20	0.0	0.6	1.8	2.4

Table 7. Difference of supply volumes in the *Economic Growth* and *Forest Intensification* alternatives in comparison to the *Reference* cost supply curves.

	Difference to the *Reference* curves (Mm³)				
	North	Central		South	
		East	West	East	West
<u>*Standardized Transportation*</u> <u>*Roundwood*</u>					

Cost 30 \$/m^3	33.6	16.9	13.3	3.9	3.1
Cost 35 \$/m^3	23.0	10.8	18.8	2.6	3.7
Cost 40 \$/m^3	14.9	6.5	8.3	1.1	2.0
Cost 45 \$/m^3	12.6	2.7	4.0	0.4	1.8
Standardized Transportation Residues					
Cost 30 \$/m^3	-0.1	-0.5	-2.2	0.8	0.5
Cost 35 \$/m^3	9.4	3.8	-2.2	1.1	0.1
Cost 40 \$/m^3	12.9	2.0	2.8	0.6	1.7
Cost 45 \$/m^3	6.4	0.8	2.9	0.4	1.2
Economic growth Roundwood					
Cost 30 \$/m^3	-17.8	-5.8	-11.8	-1.1	-1.2
Cost 35 \$/m^3	-10.0	-3.9	-11.6	-0.5	-2.4
Cost 40 \$/m^3	-7.4	-2.6	-7.1	-0.9	-2.2
Cost 45 \$/m^3	-5.7	-2.2	-6.2	-0.6	-2.2
Economic growth Residues					
Cost 30 \$/m^3	-0.6	-0.8	-1.3	-0.2	-0.4
Cost 35 \$/m^3	-3.1	-0.8	-1.8	-0.2	-1.0
Cost 40 \$/m^3	-2.6	-0.9	-1.3	-0.2	-0.7
Cost 45 \$/m^3	-1.7	-0.4	-0.9	-0.1	-0.6
Intensification Roundwood					
Total available volume	16.8	40.1	22.7	3.9	16.7
Cost 30 \$/m^3	-34.0	15.4	-6.8	-1.0	-1.6
Cost 35 \$/m^3	-21.1	27.6	-0.3	0.1	-0.5
Cost 40 \$/m^3	-8.1	34.8	8.2	0.4	0.6
Cost 45 \$/m^3	-2.6	37.1	10.9	1.6	3.6
Intensification Residues					
Total available volume	5.7	3.1	2.5	0.4	3.0
Cost 30 \$/m^3	-0.6	-0.4	-0.9	-0.1	0.0
Cost 35 \$/m^3	-2.7	0.9	-0.4	0.0	-0.1
Cost 40 \$/m^3	-1.5	2.1	0.5	0.1	0.6
Cost 45 \$/m^3	0.2	2.8	1.2	0.2	0.9

Figure 1: Decisional flowchart for assignment of harvesting systems to SimU (the descriptions of harvesting systems are given in Table 2).

Figure 2. Cost supply curves for roundwood (on the left) and logging residues (on the right), x axis=yearly amount (M m^3), y axis= marginal supply cost at the industry gate (\$/m^3). The dots on the curves for roundwood represent the current amounts mobilized according to FAOSTAT (2013).

Figure 3. Cost supply curves for roundwood logs in the EU 28 countries, x axis=yearly amount (M m^3), y axis= marginal supply cost at the industry gate (\$/m^3)

Figure 4. Cost supply curves for logging residues (delivered as wood chips) in the EU 28 countries, x axis=yearly amount (M m^3), y axis= marginal supply cost at the industry gate ($/$m^3$).

Figure 5. Cost supply curves at roadside (i.e. excluding road transportation) for roundwood (on the left) and logging residues (on the right), x axis=yearly amount (M m^3), y axis= marginal supply cost at the roadside ($/$m^3$).

Figure 6. Cost supply curves for roundwood (on the left) and logging residues (on the right), x axis=yearly amount (M m^3), y axis= marginal supply cost at the industry gate ($/$m^3$) in the *Reference* (solid lines) and in the *Standardized Transportation* (dashed lines) alternative.

Figure 7. Cost supply curves for roundwood (on the left) and logging residues (on the right), x axis=yearly amount (M m^3), y axis= marginal supply cost at the industry gate ($/$m^3$) in the *Reference* (solid lines), *Economic Growth* (dashed lines) and *Forestry Intensification* (dotted lines) alternatives. The shadowed areas represent the expected variations in each of the EU Regions.

Annex 1. Time consumption models

Felling and processing with single grip harvester (HA)

TC= time consumption (PMmin/m^3)

Parameters: *Vs*= stem volume (m^3 over bark), S= slope (%), Clearcut (Final Felling) = FF, Conifers = C

The TC for conifers (C) is based on Nurminen et al. (2006) model for spruce, the slope correction factor is based on Hartsough et al. (2001) regression for not self-leveling cabin machinery.

$TC_{HA\ FF\ C} = (1 + 0.004 \times S + 0.00013 \times S^2) \times \left(\frac{0.412 + 0.758 \times Vs + 0.180 \times Vs^2}{Vs}\right)$; (Pmin/m^3) (Eq. 1)

In case of broadleaves (B), the TC in Eq. 1 was increased of 0.45 Pmin/m^3, the coefficient was calculated according to the extra processing time found in Spinelli et al. (2010), when comparing harvesters processing broadleaves and conifers

$TC_{HA\ FF\ B} = (1 + 0.004 \times S + 0.00013 \times S^2) \times \left(\left(\frac{0.412 + 0.758 \times Vs + 0.180 \times Vs^2}{Vs}\right) + 0.45\right)$; (Pmin/m^3) (Eq. 2)

In thinning (TH), it was assumed that the TC increases compared to FF, according to the differences between two models developed for a single grip harvester in FF and TH (Eriksson & Lindroos 2014), the relation found was: $TC_{TH} = 1.28\ TC_{FF}$.

$TC_{HA\ TH\ C} = 1.28 \times \left((1 + 0.004 \times S + 0.00013 \times S^2) \times \left(\frac{60}{4.067 + 78.623 \times Vs - 18.607 \times Vs^2}\right)\right)$; (Pmin/m^3) (Eq. 3)

$TC_{HA\ TH\ B} = 1.28 \times \left((1 + 0.004 \times S + 0.00013 \times S^2) \times \left(\left(\frac{60}{4.067 + 78.623 \times Vs - 18.607 \times Vs^2}\right) + 0.45\right)\right)$; (Pmin/m^3) (Eq. 4)

Motor-manual felling with chainsaw (MF)

Parameters: *Vs*= stem volume (m^3 over bark), S= slope (%)

The *TC* for felling conifers (C) trees in FF with a chainsaw was based on Erni et al. (2003), the effect of slope was exponentially modeled as a simplification of the original model parameters.

$TC_{MF\ FF\ C} = 1.481 \times e^{(-0.9108 + 2.4291 \times Vs^{-0.4586})} \times (1 + 0.0021 \times e^{(0.0653 \times S)})$; (Pmin/m^3) (Eq. 5)

In the case of broadleaves (B), the TC was based on (Erni et al. 2003) and the model for broadleaves was applied:

$TC_{MF\ FF\ B} = 0.00175 \times e^{(1.0 + 6.9216 \times Vs^{-0.0654})} \times (1 + 0.0021 \times e^{(0.0653 \times S)})$; (Pmin/m^3) (Eq. 6)

In thinning (TH), it was assumed that TC in FF (Eq. 10-11) would increase by 20% according to the difference in Lotz et al. (1997) models, that is $TC_{TH} = 1.2\ TC_{FF}$ (i.e. considering removal stem volume of 0.2 m^3 and a removal of 40% in basal area).

$TC_{MF\ TH\ C} = 1.20 \times \left(1.481 \times e^{(-0.9108 + 2.4291 \times Vs^{-0.4586})} \times (1 + 0.0021 \times e^{(0.0653 \times S)})\right)$; (Pmin/m^3) (Eq. 7)

$TC_{MF\ TH\ B} = 1.20 \times \left(0.00175\ e^{(1.0 + 6.9216 \times Vs^{-0.0654})} \times (1 + 0.0021 \times e^{(0.0653 \times S)})\right)$; (Pmin/m^3) (Eq. 8)

Motor-manual felling and processing with chainsaw (MFP)

The TC for felling and processing with chainsaw was based on the model of Stampfer et al. (2002) (i.e. no accumulation of branches). The percentage of branches (on whole tree volume) was fixed to 20% for broadleaves and 25% for conifers in FF and respectively to 25 and 30% in TH (c.f. Lehtonen et al. 2004). The effect of slope was exponentially modeled as in Eq. 5-8.

$$TC_{\text{MFP FF C}} = \frac{0.75}{Vs} \times \left(\left(3.3229 + 9.8999 \times \left(\frac{Vs}{0.75} \right)^{0.7} \right) \times \left(1 + 0.0021 \times e^{0.0668 \times S} \right) \right)$$ (Pmin/m^3) (Eq. 9)

$$TC_{\text{MFP FF B}} = \frac{0.80}{Vs} \times \left(\left(3.3229 + 9.3564 \times \left(\frac{Vs}{0.80} \right)^{0.7} \right) \times \left(1 + 0.0021 \times e^{0.0668 \times S} \right) \right)$$ (Pmin/m^3) (Eq. 10)

In thinning (TH), it was assumed that TC in FF would increase by 20%, according to the differences measured in Lotz et al. (1997), that is $TC_{TH} = 1.2\ TC_{FF}$ (.e. considering removal stem volume of 0.2 m^3 and a removal of 40% in basal area).

$$TC_{\text{MFP TH C}} = 1.20 \times \left(\frac{0.70}{Vs} \times \left(\left(3.3229 + 10.4434 \times \left(\frac{Vs}{0.70} \right)^{0.7} \right) \times \left(1 + 0.0021 \times e^{0.0668 \times S} \right) \right) \right)$$

(Pmin/m^3) (Eq. 11)

$$TC_{\text{MFP TH B}} = 1.20 \times \left(\frac{0.75}{Vs} \times \left(\left(3.3229 + 9.8999 \times \left(\frac{Vs}{0.75} \right)^{0.7} \right) \times \left(1 + 0.0021 \times e^{0.0668 \times S} \right) \right) \right)$$ (Pmin/m^3)

(Eq. 12)

Forwarding roundwood to roadside with a forwarder (FO)

The TC model for forwarding in FF was based on Brunberg (2004). The slope effect was based on Hartsough et al. (2001) regression for not self-leveling cabin machinery, the results from the original regression were increased by 15%, as the difference found when comparing TCs from Brunberg (1995) & Brunberg (2004) for harvesters and forwarders as function of slope. The forwarder's load size in FF was fixed to 14 m^3 solid.

Parameters: *Vr*= removal volume (m^3 over bark/ha), Ls= load size (m^3 solid), *Df* = extraction distance[11] (m) (fixed to 300 m), S= slope (%)

$TC_{FO\ FF}$ =

$$\left(1 + 0.0046 \times S + 0.00015 \times S^2\right) \times 0.704 \times \left(\left(\frac{6.477 + 0.73\ Vr + 13.011 \times (Vr \times 0.88)^{0.5}}{Vr} \right) + \frac{0.0202 \times 2Df}{Ls} + 0.222 \right)$$;

(Pmin/m^3) (Eq. 13)

[11] The "extraction distance" is the distance from the stump to the roadside. It is set to 300 m for altitudes below 600 m and for wheeled machinery it increases for higher altitudes (classes) in the model:

If altitude < 300 m	Extraction distance is set to	300 m
// 300-600 m	//	300 m
// 600-1100 m	//	500 m
// 1100-1500 m	//	700 m
// >2500 m	//	1000 m

In case of TH, the TC was based on Brunberg (2004) model (Eq. 13) and the TC for terminal operations was increased by 40% as the difference measured with Brunberg's (2004) models in TH and FF (i.e. considering removal volume (Vr) of 100 m^3/ha and forwarding distance (Df) of 300 m. The load size in TH was fixed to 10 m^3 solid.

$$TC_{FO\ TH} = \left(\left(1 + 0.0046 \times S + 0.00015 \times S^2\right) \times 0.704 \times \left(1.4 \times \left(\frac{\left(6.477 + 0.73\,Vr + 13.011 \times (Vr \times 0.88)^{0.5}\right)}{Vr}\right) + \frac{0.0202 \times 2Df}{Ls} + 0.222\right)\right);$$

(Pmin/m^3) (Eq. 14)

Extraction of logs with a farm tractor (FT)

In case of extraction of logs with a farm tractor equipped with forest trailer, the time consumption of a forwarder (Eq, 13-14) was increased by a 15% at forwarding distance of 300 m, the slope factors were applied as for a forwarder. For longer distances than 300 m, the time consumption was calculated by assuming a 20% smaller load size than a forwarder according to Spinelli et al. (2015) and a 50% higher speed.

Skidding logs with a skidder (SKL)

The time consumption per working cycle in a final felling (FF) for a skidder was based on Borz et al. (2014) models. The number of stems per cycle in a final felling was fixed to "3" and the relation between stem volume and load volume per skidding cycle were calculated according to Kluender et al (1997). The slope effect for a rubber skidder was calculated from Olsen & Gibbons (1983) relation and added to the model.

Parameters: *Vs*= stem volume (m^3 over bark), *Df* = extraction distance (m) (fixed to 300 m), S= slope (%)

$$TC_{SKL\ FF} = \left(\frac{168.020 + 1.88 \times Df}{0.472 \times \left(17.540 \times Vs^{0.576}\right)^{1.041}}\right) \times 0.588 + 0.043 \times S$$; (Pmin/m^3) (Eq. 15)

In the case of thinning (TH), the time consumption in FF was increased according to the difference noticed by Kluender et al (1997), when considering a removal of 40% in basal area, that is a 35% extra time.

$$TC_{SKL\ TH} = 1.35 \times \left(\frac{168.020 + 1.88 \times Df}{0.472 \times \left(17.540 \times Vs^{0.576}\right)^{1.041}}\right) \times 0.588 + 0.043 \times S$$; (Pmin/m^3) (Eq. 16)

Skidding whole trees with a skidder (SKW)

In the case of skidding whole trees in a final felling, the same model as in SKL (Eq. 15) was applied and the "whole tree volume" in the model was calculated as $\frac{Vs}{0.775}$.

$$TC_{SKL\ FF} = \left(\frac{168.020 + 1.88 \times Df}{0.472 \times \left(17.540 \times \left(\frac{Vs}{0.775}\right)^{0.576}\right)^{1.041}}\right) \times 0.588 + 0.043 \times S$$; (Pmin/m^3) (Eq. 17)

In thinning the same model as in Eq. 16 was applied and the "whole tree volume" was calculated as $\frac{Vs}{0.726}$

$$TC_{SKL\ FF} = 1.35 \times \left(\frac{168.020 + 1.88 \times Df}{0.472 \times \left(17.540 \times \left(\frac{Vs}{0.726}\right)^{0.576}\right)^{1.041}}\right) \times 0.588 + 0.043 \times S$$; (Pmin/m^3) (Eq. 18)

Cable yarding roundwood logs (CYL)

The time consumption is based on Kühmaier (2013) & Stampfer et al. (2003) models, the piece volume used in the functions was modeled from the stem volume by logarithmic relation.

Parameters: *Vs*= stem volume (m^3 over bark), *Df* = extraction distance (m) (fixed to 300 m), S= slope (%)

TC $_{CYL\ FF}$ = $-0.7548 + 0.0122 \times Df + 0.7782 \times \left(\frac{Vs}{(1.4166 \times \ln(Vs) + 6.6186)}\right)^{-1.06} + 0.0377 \times S$; (Pmin/m^3) (Eq. 19)

In thinning (TH) for logs, the TC was assumed to increase by half the time increase recorded for "Tree-Length" extraction in TH compared to FF (c.f. Stampfer et al. 2003).

TC $_{CYL\ TH}$ = $0.01 + 0.0122 \times Df + 0.7782 \times \left(\frac{Vs}{(1.4166 \times \ln(Vs) + 6.6186)}\right)^{-1.06} + 0.0377 \times S$; (Pmin/$m^3$) (Eq. 20)

Cable yarding whole trees (CYW)

The TC for extraction of whole trees with a cable yarder was based on Ghaffariyan et al. (2009) model for a "Syncrofalke" cable yarder, the average load size was fixed to 1 m^3 in FF and the corridor side distance was fixed to 10 m. The "whole tree volume" in the model was calculated as $\frac{Vs}{0.776}$.

Parameters: *Vs*= stem volume (m^3 over bark), *Df* = extraction distance (m) (fixed to 300 m), S= slope (%)

TC $_{CYW\ FF}$ = $2.72 + 0.005 \times Df + 0.601 \times \left(\frac{Vs}{0.776}\right)^{-0.3} + 0.038 \times S$; (Pmin/m^3) (Eq. 21)

In the case of TH, the same model as in FF was applied, by setting the thinning intensity to 30%, the cable yarder load volume was set to 0.5 m^3 and the "whole tree volume" was calculated as $\frac{Vs}{0.726}$.

TC $_{CYW\ TH}$ = $2.92 + 0.01 \times Df + 1.202 \times \left(\frac{Vs}{0.726}\right)^{-0.3} + 0.076 \times S$; (Pmin/m^3) (Eq. 22)

Mechanized processing at the roadside (crosscutting and delimbing) with excavator mounted processor head (PCH)

The TC for a processor mounted on excavator was calculated with the model of Hartsough et al. (2001), the model was built on conifers. Therefore, the TC was increased by 10% in the case of broadleaves. The "DBH" used in the original function was exponentially modeled as function of stem volume.

Parameters: *Vs*= stem volume (m^3 over bark)

TC $_{PCH\ C}$ = $\frac{0.141 + 0.366 \times Vs^{0.3068}}{Vs}$; (Pmin/m^3) (Eq. 23)

TC $_{PCH\ B}$= $1.1 \times \frac{0.141 + 0.366 \times Vs^{0.3068}}{Vs}$; (Pmin/$m^3$) (Eq. 24)

Motor-manual processing at the roadside (cross-cutting and delimbing) with chainsaw (PCM)

The time consumption was obtained as the difference of the TC for felling and processing and the TC for felling (i.e. TC $_{PCM}$= $TC_{MFP} - TC_{MF}$). The obtained TC was reduced by 10% in order to account for the easier conditions at the roadside compared to the forest terrain.

Parameters: *Vs*= stem volume (m^3 over bark)

TC $_{PCM\ C}$ = $4.3431 \times Vs^{-0.662}$; (Pmin/$m^3$) (Eq. 25)

TC $_{PCM\ B}$ = $6.6472 \times Vs^{-0.675}$; (Pmin/$m^3$) (Eq. 26)

Piling logging residues with a harvester (HA_{LR})

A regression for calculating the extra time needed for piling logging residues in a separate pile was based on differences found by Brunberg (2007) for final fellings and Di Fulvio & Bergström (2013) in thinnings, compared to roundwood production. The time was assumed to be exponentially related to the stem volume:

Parameters: *Vs*= stem volume (m^3 over bark)

$TC_{HA\ LR} = 0.0026 \times Vs^{-2.064}$; (Pmin/m^3) (Eq. 27)

Motor-manual piling logging residues (MFP_{LR})

The extra time for piling logging residues in case of motor-manual felling and processing was modeled according to the differences measured by Stampfer et al. (2002) when comparing conventional roundwood production, and by assuming an exponential relation with the stem volume.

Parameters: *Vs*= stem volume (m^3 over bark)

$TC_{MFP\ LR} = 1{,}211 \times Vs^{-0.300}$; (Pmin/m^3) (Eq. 28)

Piling logging residues at roadside with a processor (PCH_{LR})

The extra time needed for a processor for piling logging residues at the roadside was assumed

$TC_{PCH\ LR} = 0.5$ (min/m^3)

Piling logging residues at roadside in motor-manual operation (PCM_{LR})

The extra time needed in motor-manual operations for piling logging residues at the roadside was assumed

$TC_{PCM\ LR} = 2.0$ (min/m^3)

Forwarding logging residues with a forwarder (FO_{LR})

The TC for forwarding logging residues to roadside was based on Brunberg & Eliasson (2011) and Nurmi (2007) model. The slope effect was assumed as in Eq. 13-14. The forwarder load size was fixed to 9.65 m^3 solid:

Vr= removal volume (m^3/ha), *Df* = forwarding distance (m) (fixed to 300 m), S= slope (%)

$TC_{FO\ LR\ FF} = ((1 + 0.0046 \times S + 0.00015 \times S^2) \times (11.944 \times Vr^{-0.324} + 0.0048 \times Df))$; (Pmin/$m^3$) (Eq. 29)

In TH, the time consumption was based on Laitila et al. (2007) and Nurmi (2007), load size was fixed to 8.45 m^3 solid:

$TC_{FO\ LR\ TH} = ((1 + 0.0046 \times S + 0.00015 \times S^2) \times (2.925 \times Vr^{-0.106} + 0.0048 \times Df))$; (Pmin/$m^3$) (Eq. 30)

Forwarding logging residues with a farm tractor (FT_{LR})

According to the assumptions for extraction of roundwood, also in the case of logging residues, the time consumption was obtained by increasing of 15% the time consumption of a forwarder at 300m, given in eq. 29-30, and by applying the same assumption made in case of roundwood for modeling effects of distance and slope.

Chipping logging residues (CH)

The TC for chipping logging residues was based on the model from Ghaffariyan et al. (2013), the machine power was set to 400 kW, in case of a truck mounted chipper with a container discharge, and the piece size was set to 0.02 m^3.

Parameters: Ps= piece size (it is fixed to 0.02 m^3)

$TC_{CH} = \frac{60}{\left(\frac{\text{[illegible]}}{\text{[illegible]}}\right)}$; (Pmin/m^3) (Eq. 31)

Time consumption for roundwood (WD) transportation (TR) with truck and trailer

The time consumption (TC) model for truck transportation was based on Nurminen and Heinonen (2007) as the average time for transporting pulpwood and sawlogs. The model was intended for a truck and trailer equipped with the crane (i.e. self-loading). The truck load capacity and road transportation distances are considered as variables in the model.

TC=time consumption (min/m^3)[12]

Parameters:

Lc= load capacity of a truck and trailer unit (m^3 solid) in the country (j) given by Annex 2.

Dt = transportation distance (km) from a forest stand to a conversion facility as given by a GIS calculations in a 5 km forest grid.

$TC_{TR\,WD} = 1.60 + \frac{20.610}{Lc} + \frac{(16.972 + 1.656 \times Dt)}{(Lc)}$; (min/m^3) (Eq. 32)

Time consumption for wood chips (WC) transportation (TR) with a container truck and trailer

A truck and trailer with 2-3 container (i.e. the number of containers was Country adjusted according to the maximum load capacity limits) was considered; no crane was considered on the truck (i.e. chips are loaded into containers from a chipper-truck during chipping operations). The loading of containers was assumed to be made from the ground with a hook equipment installed on the truck. The terminal time consumption was based on Johansson & Liss (2006).

Factors: *Lc*= truck load capacity (m^3 solid) in the country (j) given in Annex 2.

Dt = transportation distance (km) from a forest stand to a facility as given by the GIS calculations in a 5 km forest grid.

$TC_{TR\,WC} = 1.76 + \frac{7.880}{Lc} + \frac{(16.972 + 1.656 \times Dt)}{(Lc)}$; (min/m^3) (Eq. 33)

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[12] In the case of road transportation, the delays were included into the time consumption model as conventional practice for this operation.

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Annex 2. Technical utilization factors for machinery/equipment included in the selected harvesting systems.

Machinery	Sv Salvage value (ratio on Pc[13])	*EEL* Economic life (years)	SMH Annual utilization (SMH/year)	*U* Utilization rate (PMH/SMH)[14]	Reference[15]
Harvester	0.2	7.2	2500	0.79	Eriksson & Lindroos 2014
Chainsaw	0.1	2.1	1680	0.50	Miyata 1980
Forwarder	0.2	6.3	2500	0.84	Eriksson & Lindroos 2014
Farm Tractor	0.2	5.9	1680	0.65	Miyata 1980

[13] Pc=Purchase price

[14] PMH= Productive Machine Hour; SMH= Scheduled Machine Hour

[15] References for utilization rates:

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Skidder	0.2	8.5	1680	0.70	Holzleitner et al. 2011
Cable yarder	0.2	8.1	1680	0.66	Holzleitner et al. 2011
Chipper	0.2	6.0	2000	0.75	Brinker et al. 2002
Processor on excavator	0.2	8.0	1680	0.67	Miyata 1980

Annex 3. Machinery costs parameters collected in the Reference countries *(Sweden=SWE, Austria=AT)* for most relevant systems in the EU.

Machinery	Purchase price (*Pc*) (1000 $)	Ratio to harvester (*Rpc*)	Interest rate (*r*) %	Annual insurance (% *Pc*)	Other fixed costs[1] ($/SMH)	Fuel consumption (*fc*) (l/PMH)	Fuel price (*fp*) ($/l)	Lubricant cost (% fuel cost)	Maintenance (% *Pc*)	Wage ($/SMH)	Labor Cot/Wage
Harvester (SWE)	552	1.000	4.0	0.75	23.49	15.5	1.73	27	100	22.41	1.46
Forwarder (SWE)	419	0.758	4.0	0.75	23.49	12.4	1.73	10	80	20.27	1.46
Chipper (SWE)	678	1.229	4.0	0.45	27.15	51.1	1.73	10	70	20.27	1.46
Chainsaw (AT)	2.1	0.004	4.5	-	1.34	1.3	1.51	20	120	23.78	1.45
Farm Tractor and forest trailer (AT)	221	0.400	4.5	0.08	5.84	10.0	1.51	10	100	23.19	1.45
Skidder (AT)	326	0.591	4.5	0.05	8.34	10.5	1.51	10	80	23.19	1.45
Cable yarder (AT)	519	0.941	4.5	0.30	10.01	8.0	1.51	15	100	46.38	1.45
Processor on excavator (AT)	320	0.579	4.5	0.30	10.81	11.8	1.51	15	100	23.19	1.45

[1]It includes machinery taxes & garaging and general costs for operators (training, transportation, phone charges, and protective equipment), it is a cost assumed to be independent from country's borders. [2] SLU (Sweden) and BWF/AUSTROFOMA (Austria).

Annex 4. Cost benchmarking database for felling operations used for adaptation of unitary costs to country borders.

Country/Region	Expert & Institution
Australia	Mauricio Acuna, Mohammad Ghaffariyan, AFORA

Brazil	Saulo Guerra, Guilherme Oguri, UNESP
Canada	Luc LeBel, Shuva Hari Gautam, Pierre-Serge Tremblay, Univerity of Laval
France	Paul Magaud, Philippe Ruch, FCBA
Germany	Jörg Hittenbeck, University of Göttingen
Italy	Raffaele Spinelli, Natascia Magagnotti, CNR-IVALSA
Japan	Kazuhiro Aruga, Utsunomiya University
Latvia	Andis Lazdiņš, SILAVA
Norway	Bruce Talbot, Skogoglandskap Institute
Portugal	Helder Viana, Polytechnic Institute of Viseu Portugal
Slovenia	Nike Krajnc, SFI
South Africa	Pierre Ackerman, Simon Ackerman, Stellenbosch University
Spain	Sandra Sanchez, Elena Canga, CETEMAS
Sweden North	Ola Lindroos, SLU
Sweden	Lars Eliasson, Skogforsk
US Maine	Steve Bick, Northeast Forests, LLC
US Michigan, US Minnesota, US Tennessee	Dalia Abbas, University of Georgia
US North-West	Beth Dodson, University of Montana
US West Virginia	Jingxin Wang, West Virginia University

Annex 5. Collection of factors used in the country border adaptation of time unit costs.

Country Name	Market exchange rate (LCU/$)	PPP exchange rate (LCU/$)	Gross value added per employee (VAE) (M$/year)	ICRG	Trade tariff manifactured produtcts (Tf) (%)	Net Official Fuel price ($/l)	Price level ratio of PPP (PPP ratio)	Labor cost/wage
Austria	0.875	0.980	52	81.000	1.554	1.508	1.120	1.454
Belgium	0.875	0.987	53	75.500	1.554	1.636	1.129	1.786
Bulgaria	1.457	0.694	8	66.750	1.554	1.400	0.477	1.222
Croatia	5.536	3.769	33	64.250	2.128	1.360	0.637	1.179
Cyprus	0.875	0.782	1	66.125	1.554	1.508	0.895	1.143

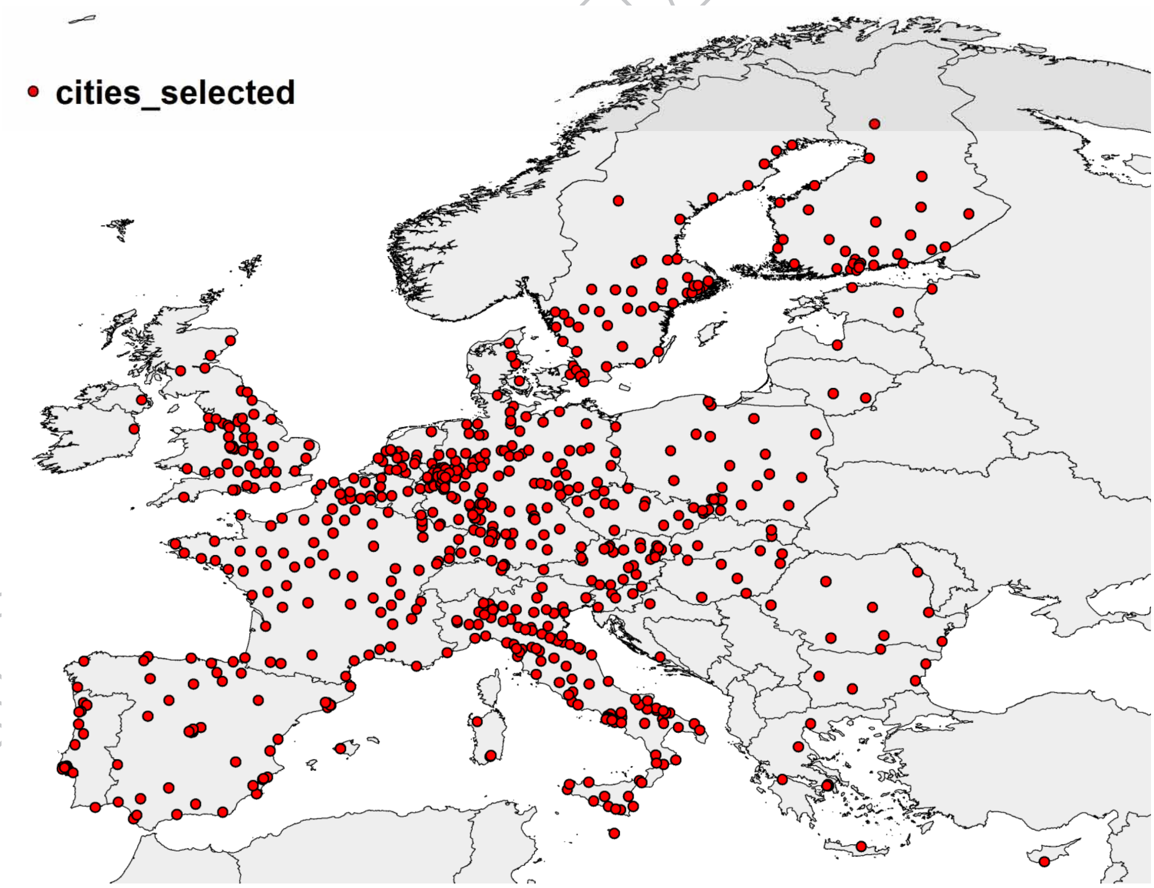
Czech Republic	19.001	13.615	54	73.000	1.554	1.545	0.684	1.515
Denmark	5.552	7.580	76	80.875	1.554	1.512	1.366	1.033
Estonia	0.875	0.639	52	71.000	1.554	1.467	0.731	1.515
Finland	0.875	1.082	161	79.625	1.554	1.573	1.237	1.282
France	0.875	0.992	121	73.500	1.554	1.488	1.134	1.736
Germany	0.875	0.922	63	81.250	1.554	1.580	1.054	1.246
Greece	0.875	0.748	18	65.875	1.554	1.691	0.856	1.379
Hungary	212.028	126.610	15	68.750	1.554	1.504	0.578	1.504
Ireland	0.875	0.966	73	74.500	1.554	1.610	1.105	1.120
Italy	0.875	0.885	30	71.750	1.554	1.787	1.011	1.555
Latvia	0.875	0.595	51	65.875	1.554	1.463	0.682	1.316
Lithuania	2.572	1.586	28	70.750	1.554	1.405	0.610	1.453
Luxembourg	0.875	1.063	170	83.875	1.554	1.426	1.215	1.149
Malta	0.875	0.869	0	73.125	1.554	1.483	0.782	1.111
Netherlands	0.875	0.962	40	78.750	1.554	1.612	1.100	1.210
Poland	3.103	1.788	38	73.000	1.554	1.407	0.576	1.389
Portugal	0.875	0.684	95	72.125	1.554	1.537	0.782	1.311
Romania	3.214	1.609	42	66.125	1.554	1.395	0.500	1.389
Slovakia	0.875	0.596	29	73.125	1.554	1.542	0.681	1.543
Slovenia	0.875	0.706	24	69.000	1.554	1.451	0.807	1.192
Spain	0.875	0.790	47	70.625	1.554	1.446	0.903	1.447
Sweden	6.929	8.879	179	83.250	1.554	1.728	1.352	1.458
UK	0.637	0.688	27	75.250	1.554	1.892	1.092	1.160

Annex 6. Number of pulpmills, biomass power plants (>0.2 MW), the applied density of facilities (average of column pulpmill and power plant) and the corresponding size of selected cities.

Country	Pulpmill (n)	Power Plant (n)	Applied density of facilities (n)	City size (population 1 000)
Austria	28	33	31	15
Belgium	14	6	10	90
Bulgaria	9	1	5	150
Croatia	3	0	2	150
Cyprus	0	0	1	70
Czech Republic	26	9	18	54
Denmark	4	8	6	55
Estonia	4	1	3	60
Finland	51	7	29	31
France	129	24	77	99
Germany	192	87	140	62
Greece	16	0	8	95

Hungary	11	5	8	105
Ireland	0	2	1	130
Italy	214	17	116	53
Latvia	1	1	1	120
Lithuania	4	0	2	200
Luxembourg	0	0	1	30
Malta	0	0	1	20
Netherlands	23	11	17	124
Poland	45	0	23	155
Portugal	31	11	21	46
Romania	14	1	8	250
Slovakia	8	0	4	87
Slovenia	8	0	4	30
Spain	92	11	52	113
Sweden	57	40	49	22
United Kingdom	63	38	51	122

Annex 7. Map of selected cities as a proxy of woody biomass conversion facilities.



Annex 8: Adaptation of transportation costs across the country borders.

The truck and trailer fixed costs *(Cf)* in a country (j) is given by the sum of interests and the other fixed costs (*cfa*) as:

$$cf_{ij}=cfa_t+\left\{\frac{\frac{Pca_{ij}\times(1-Sv_a)}{2}+Pca_{ij}\times Sv_a}{SMH_t}\right\}\times r_j+\left\{\frac{\frac{Pcb_{ij}\times(1-Sv_b)}{2}+Pcb_{ij}\times Sv_b}{SMH_t}\right\}\times r_j$$

(*i=operation; j=country*) ($/SMH) (Eq. 1)

Pc_a= Purchase price for the truck used in operation (i) in Country (j);

Pc_b= Purchase price for the trailer used in operation (i) in Country (j);

Sv_a= Salvage value as percentage of purchase price for truck = 0.1;

Sv_b= Salvage value as percentage of purchase price for trailer = 0.07;

SMH_t =Annual utilization of truck and trailer = 3500 SMH;

The kilometric depreciation (cvk) for a truck and trailer in the country (j) is given by:

$$cvk_{ij}=\frac{Pca_{ij}\times(1-Sv_a)}{lf_a}+\frac{Pcb_{ij}\times(1-Sv_b)}{lf_b}$$ (*i=operation; j=country*) ($/km) (Eq. 2)

lf_a= truck life length in km = 1 000 000 km;

lf_b= trailer life length in km = 1 500 000 km;

The depreciation for crane (*cc*) is calculated according to:

$$cc_j=\frac{Pcc_j\times(1-Sv_c)}{lf_c}$$ ($/load) (Eq. 3);

Pcc_j= Purchase price for the crane in Country (j);

Sv_c = Salvage value as percentage of purchase price for crane = 0.07

lf_c = crane life length in number of loads = 5 000 loads

The total cost for road transportation in a generic country (j) is given by:

$$\text{Transportation Cost}=\frac{(cf_{ij}+cl_{ij})\times tc_i}{60}+\frac{[(fc\times fp_j)+cvk_{ij}]\times 2dt_x+[(cc_j\times 1.3)+(fcc\times fp_j)]}{Lc_{ij}};$$

(*i=operation (WD/CH); j=country; x= harvesting unit*) ($/m^3) (Eq. 4)

tc_i= time consumption for operation (i), given in Annex 1.

cf_{ij}= fixed hourly cost for operation (i) in the Country (j), given by Eq. 1.

cl_i= total labor hourly cost for operation (i) in the country (j) (sum of wage and social charges).

fc_i = fuel consumption for driving in operation (i), given in Annex 10.

fcc = fuel consumption for crane work given in Annex 10.

fp_j= fuel price in the Country (j).

cvk_{ij}= Kilometric depreciation for truck and trailer for operation (i) in the Country (j), given by Eq. 2.

Lc_{ij} = load capacity (m^3 solid) for truck and trailers in operation (i) in each country (j) given by Annex 9.

dt_x = transportation distance (km) from forest roads to conversion facilities, explicitly calculated as the shortest route from the center of each SimU to the closest conversion facility in each country.

Annex 9. Load capacities *(Lc)* for a truck and trailer calculated in the EU Countries, according to the Country limitations and the products (payload limitation sourced from EU (2014)[16]).

Country	WD Roundwood (m^3 solid)[17]	WC Woodchips (m^3 solid)[18]
Austria	26	19
Belgium	31	24
Bulgaria	26	19
Croatia	26	19
Cyprus	26	19
Czech Republic	31	24
Denmark	33	28
Estonia	26	19
Finland	45	32
France	26	19
Germany	26	19
Greece	26	19
Hungary	26	19
Ireland	31	24
Italy	31	24
Latvia	26	19
Lithuania	26	19
Luxembourg	31	24
Malta	26	19
Netherlands	35	31
Poland	26	19
Portugal	26	19
Romania	26	19
Slovakia	26	19
Slovenia	26	19

[16] European Commission 2014. EU transport in figures. Statistical Pocketbook 2014. Publications Office of the European Union, 2014. http://ec.europa.eu/transport/facts-fundings/statistics/index_en.htm

[17] Density of roundwood = 850 fresh kg m^{-3}

[18] Density of woodchips = 900 fresh kg m^{-3}

Spain	26	19
Sweden	45	32
United Kingdom	31	24

Annex 10. Cost parameters for truck transportation in the Reference country (Ref) (Reference Sweden, SLU).

Type	Purchase price truck *(Pca)*	Purchase price trailer *(Pcb)* (1000 $)	Purchase price crane (Pcc) ($)	Ratio to harvester for truck *(Rpc)*	Ratio to harvester for trailer *(Rpc)*	Ratio to harvester for crane *(Rpc)*	Other fixed costs *(cfa)*[1] ($/SMH)	Fuel consumption Crane *(fcc)* (l/load)	Fuel consumption for driving *(fc)* (l/km)	Fuel price *(fp)* ($/l)	Wage ($/SMH)	Labor cost/Wage
Truck and trailer wood	224	79	73	0.405	0.144	0.131	9.03	4.5	0.56	1.73	22.04	1.46
Container truck and trailer wood-chips	224	137	-	0.405	0.248		9.03	-	0.56	1.73	22.04	1.46

[1] It includes machinery taxes & garaging and other general cost

Annex 11. Values used for adaptation of future labor costs and fuel prices in 2030 in the "*Economic growth* and *Forest Intensification*" sensitivity analysis.

Country Name	Increase of GDP per capita (%)	Price level ratio of PPP (PPP ratio)	Net Official Fuel price ($/l)
Austria	18	1.323	1.609
Belgium	14	1.291	1.741
Bulgaria	40	0.669	1.494
Croatia	29	0.825	1.449
Cyprus	14	1.018	1.602
Czech Republic	31	0.895	1.648
Denmark	19	1.625	1.605
Estonia	45	1.060	1.566
Finland	18	1.462	1.676
France	22	1.388	1.584
Germany	17	1.228	1.686
Greece	19	1.017	1.797
Hungary	29	0.743	1.599
Ireland	34	1.481	1.705
Italy	17	1.186	1.896
Latvia	53	1.043	1.554
Lithuania	38	0.840	1.499
Luxembourg	14	1.389	1.520
Malta	29	1.011	1.578
Netherlands	16	1.278	1.717
Poland	38	0.796	1.499
Portugal	27	0.991	1.633
Romania	32	0.663	1.488
Slovakia	40	0.957	1.637
Slovenia	25	1.007	1.549
Spain	33	1.200	1.544
Sweden	20	1.616	1.837
UK	22	1.330	2.021

Annex 12. Descriptive statistics of the cost supply curves in the sensitivity analyses

Standardized transportation

Roundwood

	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	20.98	0.0	7.6	12.3	20.0
Belgium	21.57	0.0	4.7	5.8	5.8
Bulgaria	17.38	2.6	5.1	5.6	6.3
Croatia	17.24	3.4	5.7	6.0	6.2
Cyprus	25.40	0.0	0.0	0.0	0.0
Czech	17.28	13.2	20.2	20.2	20.3
Denmark	18.88	1.1	2.9	3.1	3.1
Estonia	19.63	0.9	9.8	10.3	10.7
Finland	22.62	0.1	43.7	59.2	75.3
France	23.79	0.0	46.7	84.6	98.4
Germany	20.19	0.3	81.7	84.5	84.9
Greece	28.73	0.0	0.2	0.4	1.6
Hungary	19.05	1.3	7.3	7.8	7.9
Ireland	18.71	0.7	3.0	3.2	3.4
Italy	23.54	0.0	4.0	7.0	14.1
Latvia	19.38	1.6	12.3	12.3	12.4
Lithuania	18.29	0.9	6.0	6.7	6.9
Netherlands	18.43	0.7	1.0	1.1	1.1
Poland	17.30	26.8	39.5	40.2	40.3
Portugal	23.39	0.0	7.2	10.7	12.3
Romania	16.87	4.1	13.1	16.5	16.6
Slovakia	19.00	0.3	5.4	7.7	7.7
Slovenia	19.26	0.1	2.8	2.9	3.0
Spain	24.26	0.1	4.7	9.4	22.5
Sweden	20.63	0.0	55.1	84.1	89.4
UK	19.62	0.1	10.6	13.0	14.2

Logging residues

	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	26.10	0.0	0.9	1.9	2.0
Belgium	26.16	0.0	0.0	0.5	0.5
Bulgaria	21.76	0.0	0.8	0.9	0.9
Croatia	22.56	0.0	0.6	0.9	0.9
Cyprus	23.89	0.0	0.0	0.0	0.0
Czech	22.80	0.0	0.1	2.1	2.1
Denmark	29.56	0.0	0.1	0.4	0.4
Estonia	30.28	0.0	0.1	1.9	2.0
Finland	32.06	0.0	0.1	13.4	13.6
France	25.60	0.0	0.8	7.0	10.9
Germany	25.74	0.0	2.3	8.1	8.1
Greece	26.01	0.0	0.1	0.2	0.2
Hungary	23.48	0.0	0.7	1.4	1.4
Ireland	24.03	0.0	0.0	0.4	0.5
Italy	25.65	0.0	0.7	1.8	1.8
Latvia	30.07	0.0	0.1	1.8	1.8
Lithuania	28.37	0.0	0.9	1.4	1.5
Netherlands	31.43	0.0	0.0	0.1	0.1
Poland	22.74	0.0	0.2	3.4	3.4
Portugal	25.32	0.0	0.2	1.7	1.8
Romania	22.65	0.0	0.7	1.3	1.3
Slovakia	24.40	0.0	0.2	0.7	0.7
Slovenia	23.53	0.0	0.1	0.3	0.3
Spain	24.91	0.0	1.3	3.7	4.1
Sweden	25.76	0.0	0.1	15.7	15.8.
UK	25.27	0.0	0.1	2.4	2.4

Economic Growth

Roundwood

	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	16.16	1.5	7.6	11.6	20.0
Belgium	18.93	0.2	4.6	5.7	5.8
Bulgaria	16.13	0.9	3.3	4.7	6.3
Croatia	16.23	0.9	3.1	5.0	6.2
Cyprus	25.89	0.0	0.0	0.0	0.0
Czech	14.50	11.5	19.8	20.2	20.3
Denmark	17.95	0.7	2.6	3.1	3.1
Estonia	18.99	0.3	4.6	9.1	10.7
Finland	21.09	0.0	25.9	52.3	75.3
France	19.33	0.1	29.2	73.4	98.4
Germany	15.10	25.1	78.0	84.0	84.9
Greece	28.77	0.0	0.1	0.3	1.6
Hungary	16.53	0.6	4.7	7.3	7.9
Ireland	18.08	0.2	0.8	2.0	3.4
Italy	20.98	0.0	3.9	6.7	14.1
Latvia	24.32	0.0	1.7	7.3	12.4
Lithuania	17.51	0.5	2.8	5.5	6.9
Netherlands	16.50	0.7	1.0	1.1	1.1
Poland	13.86	6.7	29.9	39.6	40.3
Portugal	21.20	0.0	5.8	9.8	12.3
Romania	18.37	0.4	4.8	11.0	16.6
Slovakia	14.36	0.9	3.5	5.2	7.7
Slovenia	18.15	0.2	2.4	2.8	3.0
Spain	18.02	0.1	1.8	6.4	22.5
Sweden	15.69	0.9	40.4	76.3	89.4
UK	13.48	3.1	9.0	11.3	14.2

Logging residues

	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	18.91	0.0	0.9	1.8	2.0
Belgium	26.96	0.0	0.0	0.5	0.5
Bulgaria	22.58	0.0	0.2	0.7	0.9
Croatia	17.14	0.0	0.2	0.5	0.9
Cyprus	19.16	0.0	0.0	0.0	0.0
Czech	17.87	0.0	0.7	2.1	2.1
Denmark	27.75	0.0	0.1	0.4	0.4
Estonia	27.36	0.0	0.0	0.8	2.0
Finland	29.97	0.0	0.0	8.3	13.6
France	19.45	0.0	0.2	4.7	10.9
Germany	19.68	0.0	1.7	7.5	8.1
Greece	24.23	0.0	0.0	0.1	0.2
Hungary	23.39	0.0	0.3	1.0	1.4
Ireland	24.67	0.0	0.0	0.2	0.5
Italy	19.33	0.0	0.5	1.7	1.8
Latvia	33.30	0.0	0.0	0.3	1.8
Lithuania	25.10	0.0	0.2	0.8	1.5
Netherlands	28.73	0.0	0.1	0.1	0.1
Poland	20.24	0.0	0.5	2.1	3.4
Portugal	18.93	0.0	0.2	1.2	1.8
Romania	21.07	0.0	0.1	0.6	1.3
Slovakia	23.96	0.0	0.1	0.3	0.7
Slovenia	23.37	0.0	0.0	0.3	0.3
Spain	21.17	0.0	0.5	1.8	4.1
Sweden	29.79	0.0	0.0	8.6	15.8
UK	21.88	0.0	0.3	1.7	2.4

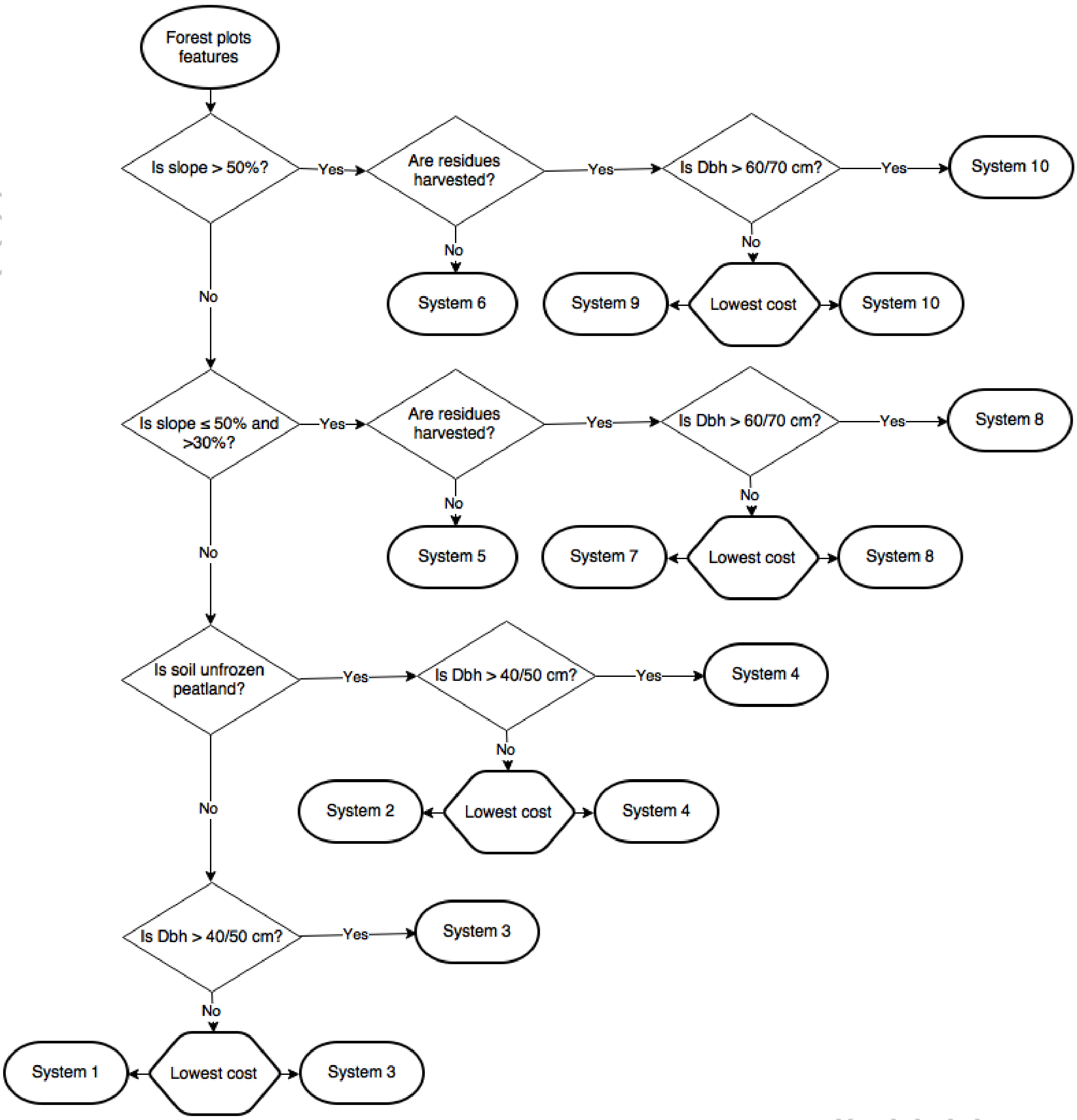
Forestry Intensification

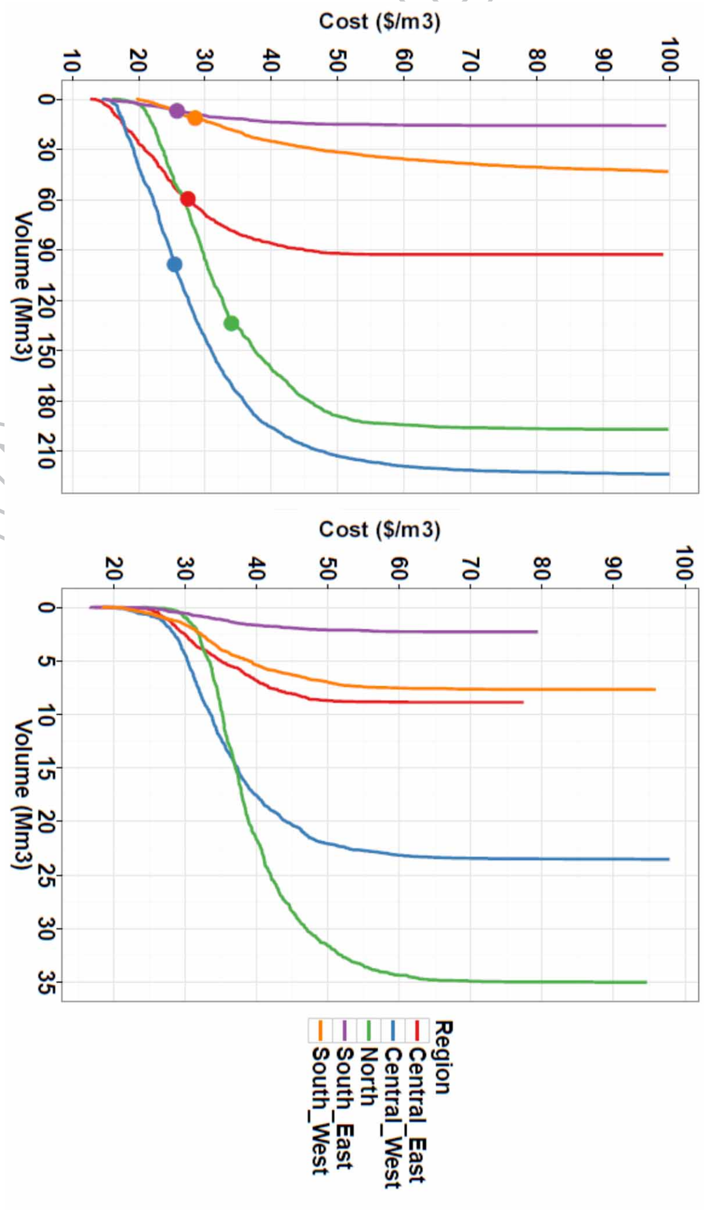
Roundwood

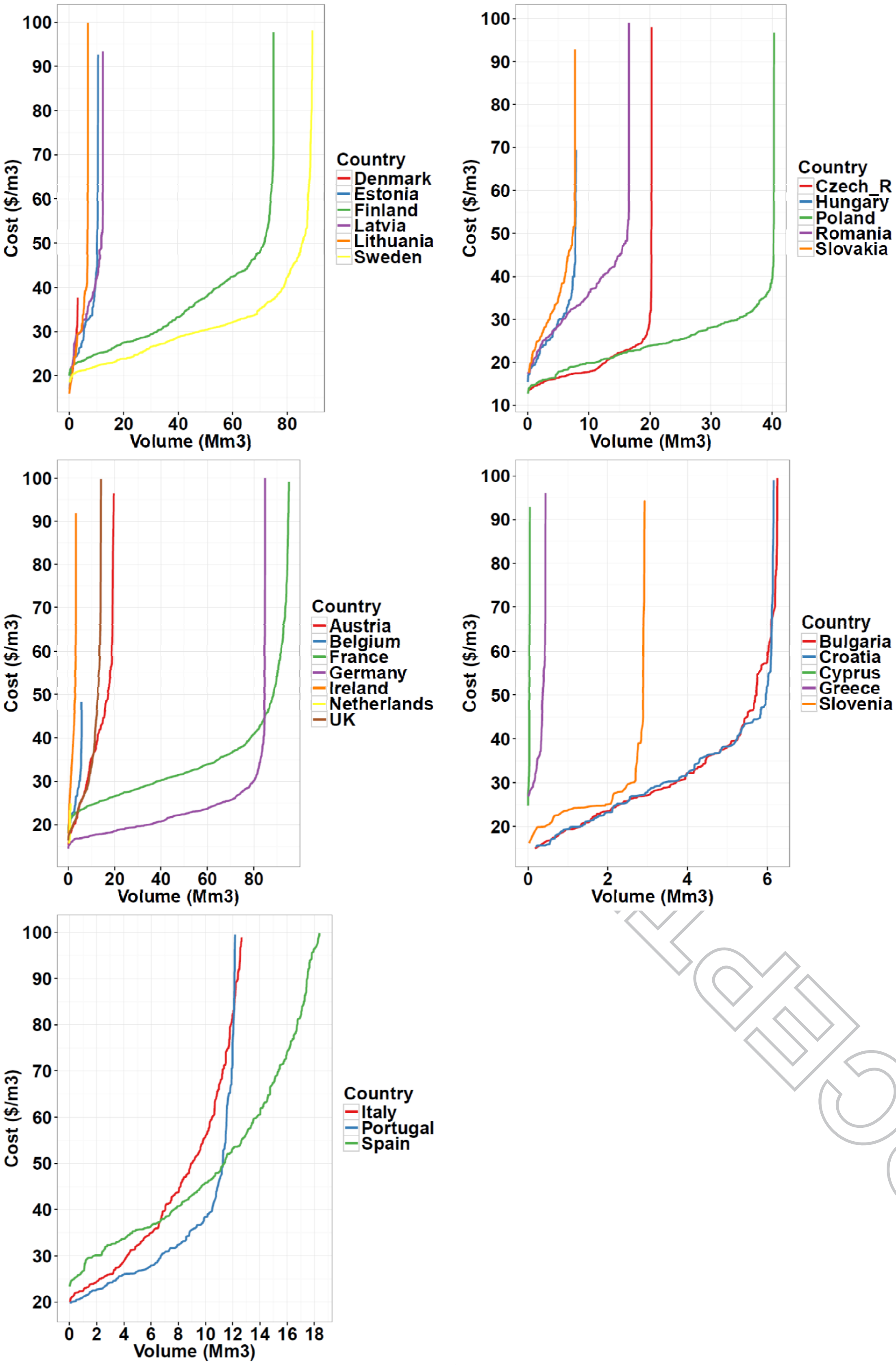
	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	15.55	1.5	7.6	11.7	21.9
Belgium	18.96	0.3	5.7	6.8	7.0
Bulgaria	14.99	0.9	3.5	5.7	7.4
Croatia	16.86	0.6	2.6	4.7	7.9
Cyprus	20.85	0.0	0.0	0.1	0.1
Czech	14.22	9.7	20.2	20.7	20.8
Denmark	16.43	0.8	3.4	4.0	4.0
Estonia	19.01	0.3	3.3	8.4	10.7
Finland	20.95	0.0	17.4	51.2	84.2
France	18.84	0.0	21.3	69.3	99.0
Germany	14.49	24.5	88.8	98.5	99.4
Greece	26.61	0.0	0.0	0.4	2.0
Hungary	15.18	0.8	8.6	12.3	13.0
Ireland	18.32	0.2	0.7	1.7	3.5
Italy	20.07	0.0	4.6	8.4	17.6
Latvia	26.60	0.0	1.6	6.2	12.3
Lithuania	17.52	0.5	3.3	7.7	10.5
Netherlands	15.42	1.6	2.5	2.5	2.9
Poland	13.59	9.2	46.5	65.6	67.2
Portugal	20.98	0.0	4.7	9.1	13.1
Romania	13.97	0.6	5.4	14.9	21.9
Slovakia	17.01	0.3	3.5	7.3	10.2
Slovenia	16.03	0.2	2.7	3.4	3.6
Spain	24.91	0.0	1.8	8.2	34.9
Sweden	19.60	0.4	33.6	75.4	92.9
UK	17.37	1.1	8.9	13.4	16.8

Logging residues

	Intercept ($/m^3)	Volume (Mm^3) mobilized at 20 $/m^3	Volume (Mm^3) mobilized at 30 $/m^3	Volume (Mm^3) mobilized at 40 $/m^3	Total Potential (Mm^3)
Austria	18.54	0.0	1.0	1.9	2.2
Belgium	17.94	0.0	0.0	0.6	0.7
Bulgaria	17.69	0.0	0.3	0.8	1.0
Croatia	17.15	0.0	0.1	0.5	1.1
Cyprus	19.16	0.0	0.0	0.0	0.0
Czech	17.87	0.0	0.8	2.1	2.2
Denmark	26.82	0.0	0.2	0.5	0.5
Estonia	27.36	0.0	0.0	0.8	1.9
Finland	22.29	0.0	0.0	8.8	15.9
France	19.30	0.0	0.2	4.6	11.2
Germany	19.68	0.0	1.8	8.6	9.3
Greece	22.33	0.0	0.0	0.1	0.3
Hungary	19.90	0.0	0.3	1.4	1.8
Ireland	24.67	0.0	0.0	0.2	0.6
Italy	19.33	0.0	0.7	2.1	2.3
Latvia	33.30	0.0	0.0	0.4	1.9
Lithuania	25.10	0.0	0.2	1.1	2.2
Netherlands	14.81	0.0	0.1	0.2	0.3
Poland	20.24	0.0	0.9	4.2	6.0
Portugal	18.93	0.0	0.2	1.2	2.0
Romania	19.35	0.0	0.2	0.9	1.7
Slovakia	22.80	0.0	0.1	0.6	1.0
Slovenia	23.37	0.0	0.1	0.4	0.4
Spain	20.43	0.0	0.8	2.6	6.5
Sweden	21.41	0.0	0.0	8.7	15.7
UK	17.76	0.0	0.4	2.1	2.9


Forest plots features
Is slope > 50%?
Yes
No
Are residues harvested?
Yes
No
Is Dbh > 60/70 cm?
Yes
No
System 10
System 6
System 9
Lowest cost
System 10
Is slope ≤ 50% and >30%?
Yes
No
Are residues harvested?
Yes
No
Is Dbh > 60/70 cm?
Yes
No
System 8
System 5
System 7
Lowest cost
System 8
Is soil unfrozen peatland?
Yes
No
Is Dbh > 40/50 cm?
Yes
No
System 4
System 2
Lowest cost
System 4
Is Dbh > 40/50 cm?
Yes
No
System 3
System 1
Lowest cost
System 3


Cost ($/m3)
Volume (Mm3)
Cost ($/m3)
Volume (Mm3)
Region
Central_East
Central_West
North
South_East
South_West


Cost ($/m3)
Volume (Mm3)
Country
Denmark
Estonia
Finland
Latvia
Lithuania
Sweden
Cost ($/m3)
Volume (Mm3)
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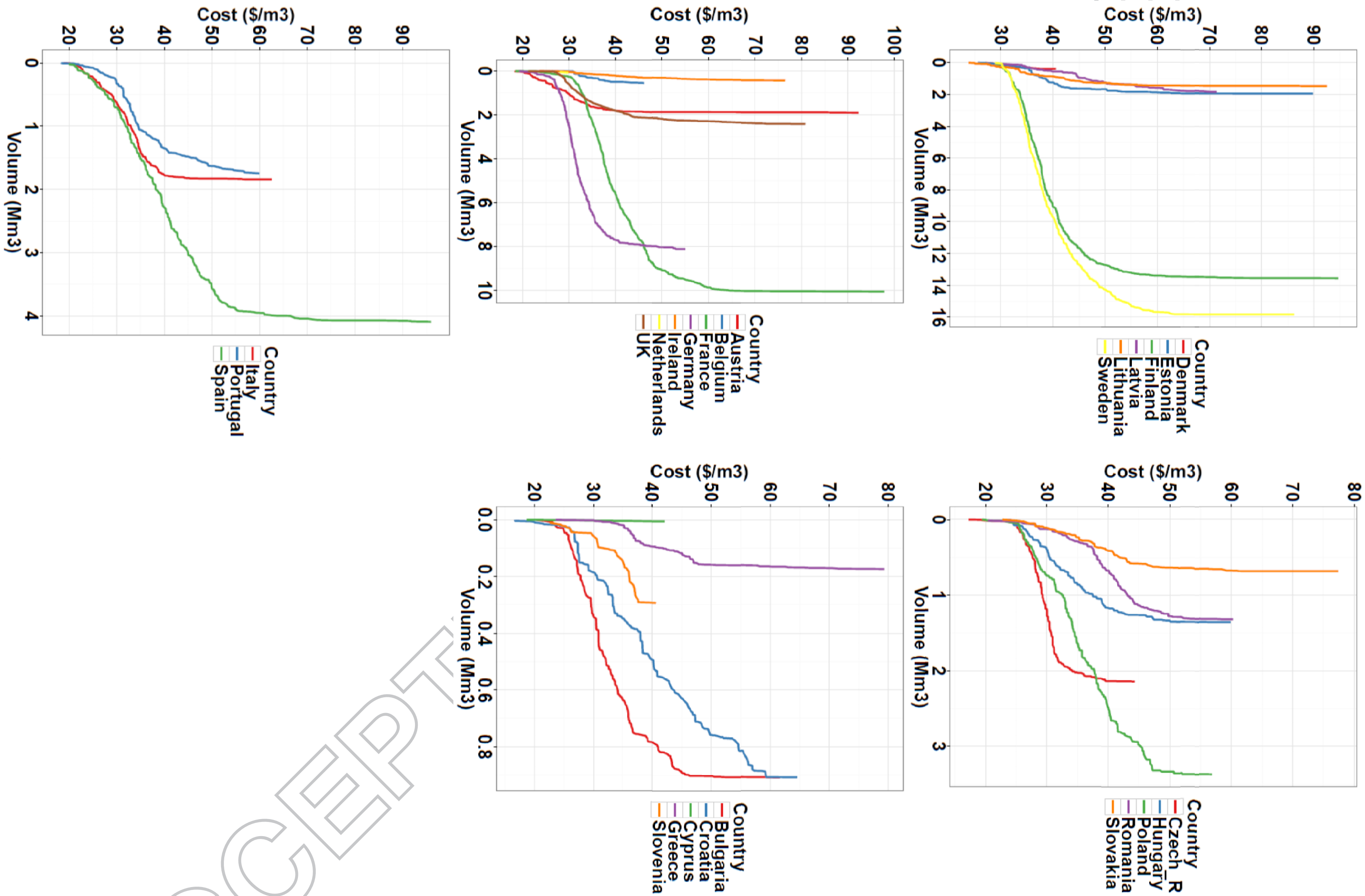
Czech_R
Hungary
Poland
Romania
Slovakia
Cost ($/m3)
Volume (Mm3)
Country
Austria
Belgium
France
Germany
Ireland
Netherlands
UK
Cost ($/m3)
Volume (Mm3)
Country
Bulgaria
Croatia
Cyprus
Greece
Slovenia
Cost ($/m3)
Volume (Mm3)
Country
Italy
Portugal
Spain


Cost ($/m3)
Volume (Mm3)
Country
Denmark
Estonia
Finland
Latvia
Lithuania
Sweden
Country
Austria
Belgium
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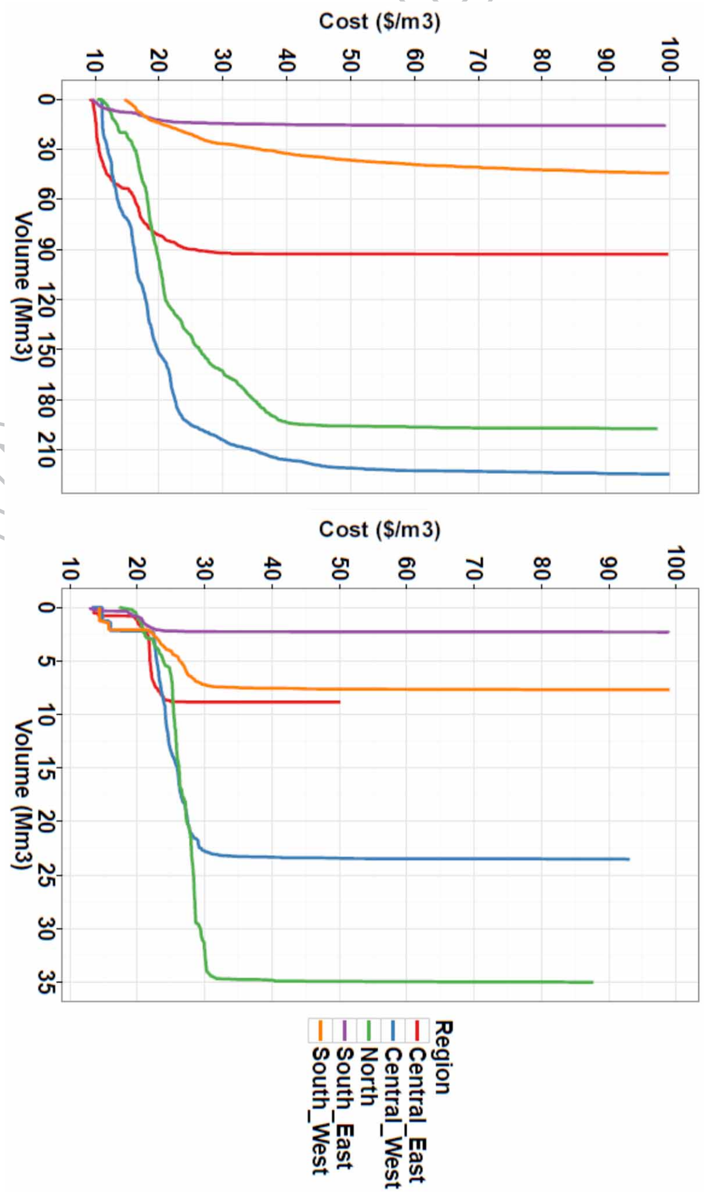
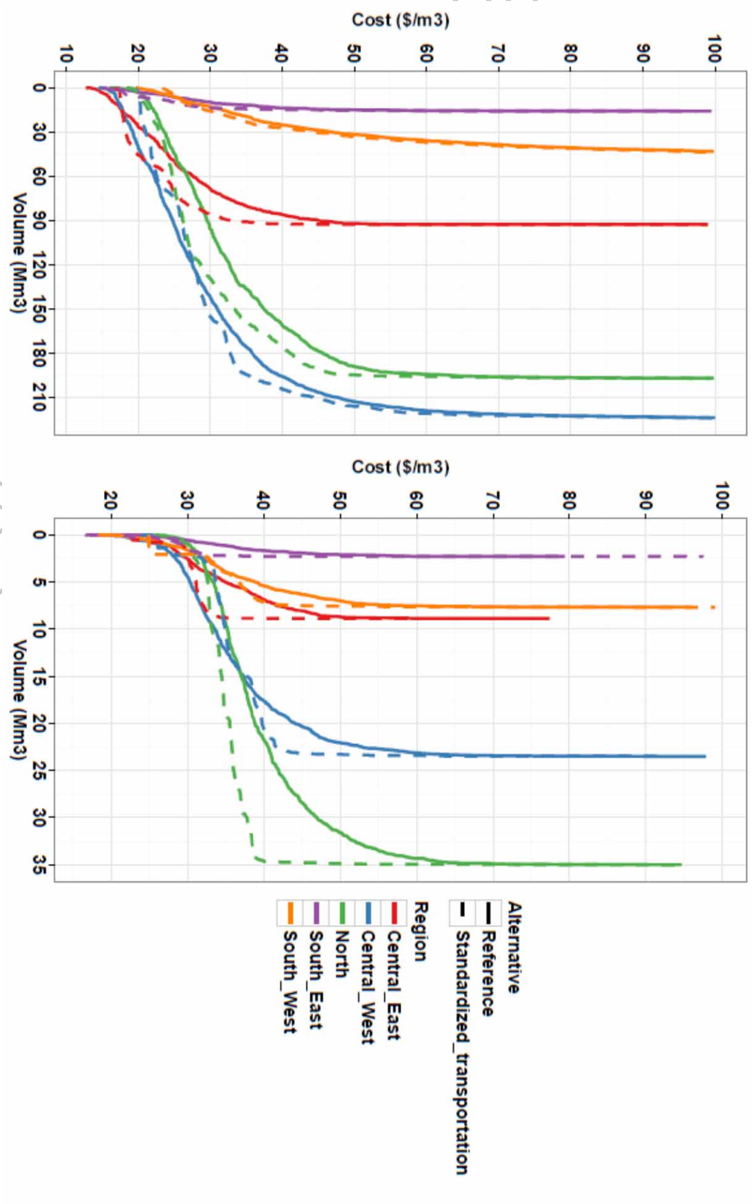
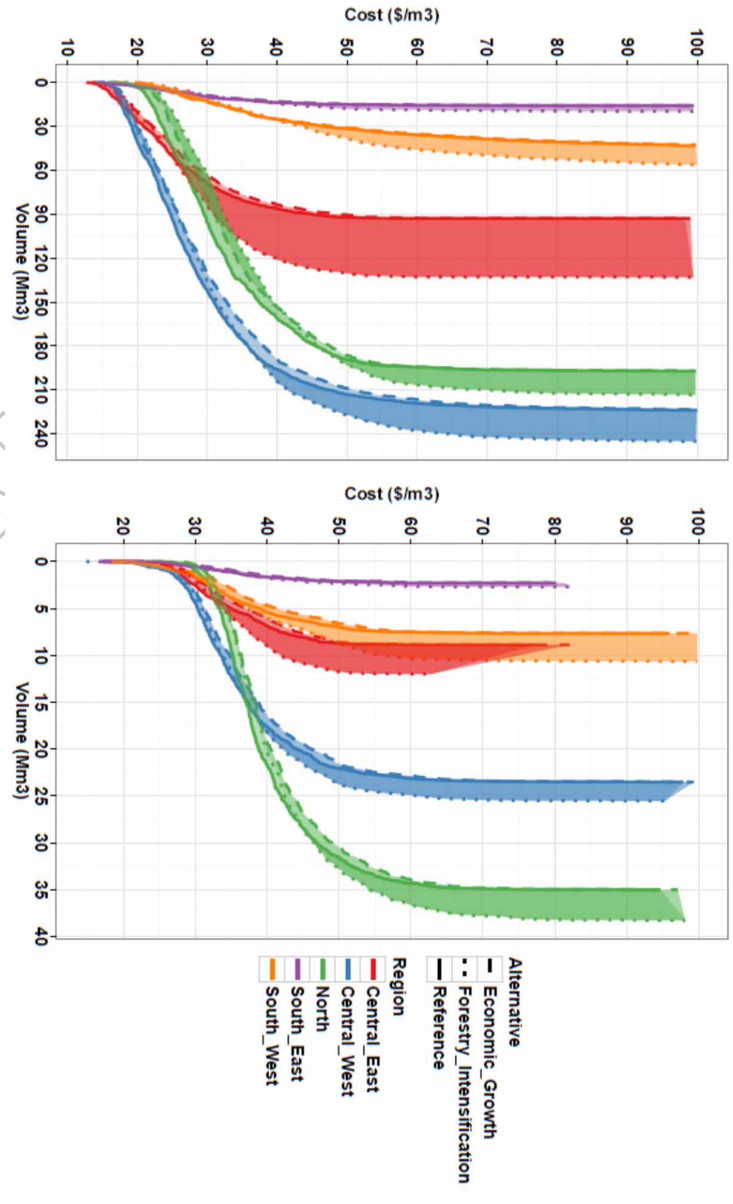
Germany
Ireland
Netherlands
UK
Country
Italy
Portugal
Spain
Country
Czech_R
Hungary
Poland
Romania
Slovakia
Country
Bulgaria
Croatia
Cyprus
Greece
Slovenia


Cost ($/m3)
Volume (Mm3)
Cost ($/m3)
Volume (Mm3)
Region
Central_East
Central_West
North
South_East
South_West



Cost ($/m3)
Volume (Mm3)
Cost ($/m3)
Volume (Mm3)
Alternative
Reference
Standardized_transportation
Region
Central_East
Central_West
North
South_East
South_West


Cost ($/m3)
Volume (Mm3)
Cost ($/m3)
Volume (Mm3)
Alternative
Economic_Growth
Forestry_Intensification
Reference
Region
Central_East
Central_West
North
South_East
South_West