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Economic evaluation of forest biomass production in central Italy: A scenario assessment based on spatial analysis tool

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ABSTRACT

A spatial analysis tool, a Decision Support (DS) model able to support decision-making processes related to forestry energy planning has been developed using ecological and economic parameters. In this paper, the relative performance of different forest energy chains were compared by using metrics such as net revenue from forest processes, break-even prices of wood fuels, and the price elasticity of the bioenergy supply. Working with different scenarios at a spatial level, the DS model can evaluate innovative technologies and traditional forest harvest and logistical chains across a range of products, such as firewood and woodchips. The spatial analysis lends itself easily to an analysis of the political and administrative constraints with respect to levels of administration and regional variables.

As expected, applying the tool to the Tuscany region in Italy shows that local characteristics and the species composition of an area influence the economic outcome of different harvest and logistical chains. In particular, mixed species Mediterranean forests appear to be suitable for the implementation of innovative bioenergy production processes, such as Whole Tree Chipping.

1. Introduction

Interest in innovative biofuels in Europe has grown in recent decades with the importance of the twin goals of reducing greenhouse gas emissions and mitigating climate change. The use of this type of energy requires consideration of a set of variables and relationships between socio-economic and environmental factors to implement sustainable bioenergy chains and avoid depletion of natural resources. Natural resource based policies and management decisions are essential to reach these goals [1] and [2].

The "Status of Biomass Resource Assessments" [3] shows an array of methodologies that have been developed to provide in-depth insight into state-of-the-art biomass resource assessments for European forests; the authors of this work analysed the heterogeneity of the results, methodologies and data sources used. These authors also offer an analysis of the relevant literature that depicts the main parameters of the evaluation and includes the following:

- type of biomass potential (ecological, technical, economical, and sustainable);
- approach (demand-driven and resource-focused);
- biomass sources (stem wood, logging residues, early thinning, and stumps);
- geographical coverage (global, national, local, etc.); and
- time frame.

Many papers focus on the quantification of biomass by spatial analysis methodology and Geographic Information

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System (GIS)). The optimal resource allocation considers logistical parameters (resource accessibility and supply chain facilities), bioenergy demand saturation, economic optimisation and carbon dioxide minimisation.

Methodologies that define the bioenergy supply/demand ratio at different administrative levels were proposed by the Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) approach [4] and by the Scale approach [5].

Moller and Nielsen [6] evaluated the optimal allocation of woodchips by minimizing transportation costs from forest areas to end-users. Panichelli and Gnansounou [7] developed an analytical methodology to allocate forest biomass in a gasification plant that implemented the BIOAL algorithm. A similar approach can be found in Frombo et al. [8], who developed a mixed non-linear programming methodology able to introduce environmental constraints in the chain evaluation of forest residues. Other economic evaluations of the production process were performed by spatial analysis and scenario assessment [9] [10], and [11]. The minimisation of the carbon footprint in the agroenergy sector was considered in Lam et al. [12] and [13] by utilizing a P-graph algorithm.

The effect of biomass extraction on forest multifunctionality was introduced to assess how it affects social perception [14] and to consider the ecological, technical and socio-economic constraints in different mobilisation scenarios [15].

In the forestry sector, the potential conflict that can be established between biomass used for energy or directed for other uses may be observed in production related to sawmill residue. Depending on the typology of the residue and the market, residues used to produce bioenergy may create a conflict with conventional uses, such as production of panels [16], [17], and [18].

Although several studies have analysed forest biomass availability, only a limited number of studies have considered the potential trade-offs in the production of different wood-energy assortments in the forestry sector. Manley and Richardson [19] investigated and reported on forest management systems in Canada, Sweden, the United Kingdom, and Switzerland. These systems included conventional organisations for managing softwood and mixed wood forests for multiple products and hardwood-oriented systems with an emphasis on the production of biomass for energy.

In this framework, this paper aims to define the potential trade-offs in a forest bioenergy production system by calculating biomass availability and economic indices.

Section 2 presents the methodological approach, the scenario assessment and spatial analysis model characteristics. In section 3, the main results of the study are presented and explained. Finally, section 4 reports conclusions and potential future studies.

2. Methodology

2.1. Study area and dataset

The model was developed and tested in Tuscany, in central Italy. Data from the recent National Forest Inventory [20] highlight that the total regional forest surface is approximately 1,151,000 ha (50.1% of the total surface). Tuscany forests are characterised by strong variations in terms of geomorphology and species composition. The main formations are deciduous broadleaved forests (79%, mainly composed by turkey oak – *Quercus cerris* L., chestnut – *Castanea sativa* Mill., and pubescens oak – *Quercus pubescens* Willd.), followed by evergreen broadleaved forests (13% composed of holm oak – *Quercus ilex* L. – and cork oak – *Quercus suber* L.) and conifers (8%) (Fig. 1). Of these forests, 80% belong to private owners. The regional forests are generally managed as coppice (63% of total and 79% of private surfaces) and are normally harvested for the production of firewood [21].

The first phase of the work was the implementation of a Territorial Informative System that includes the following themes:

- Administrative boundaries (regional and municipality boundaries);
- Corine Land Cover 2006;
- Digital Terrain Model (DTM);
- Main and forest roads;
- Tuscany Forest Inventory; and
- Municipality county seat.

The model is based on a raster analysis with a spatial resolution of 75 m per square pixel.

2.2. Scenario assessment and methodological approach

The study was based on a medium- to long-term time frame and utilised a resource-focused approach. In accordance with the issues described in chapter 1, different case studies were evaluated for the following purposes: i) estimating the total potential biomass from Tuscany forests, ii) evaluating the economic efficiency of forest processes, and iii) analysing the trade-offs between the different scenarios.

In particular, the model provided three scenarios (each a SC).

SC1 analyses forest chain organisations utilizing current technology level and without woodchip production. The hypothesis is that processing operations, such as delimbing and crosscutting, are undertaken in the forest. Extraction is provided by tractor and winch or by cable crane.

A medium-high technological level with respect to current standards will be introduced in SC2 and SC3. A Whole Tree extraction system was utilised and ground-based extraction was undertaken by skidder. Trees are processed at landing and residues (tops and branches) are chipped. When there is thinning from high forests (in SC2) and for SC3 generally, the model applies the WTC system. Furthermore, SC3 focuses only on forest stands currently used for firewood production (coppices of oak, beech – *Fagus sylvatica*, hophornbeam – *Ostrya carpinifolia* Scop., etc.).

The spatial model considers ecological biomass availability, and this amount was subsequently refined by the introduction of technical and economic constraints.

2.3. Spatial model implementation

2.3.1. Ecological biomass availability

Biomass availability may be defined as a function of the periodic annual increment of forest. This value refers to the stock of natural capital and a sustainable yield [22].

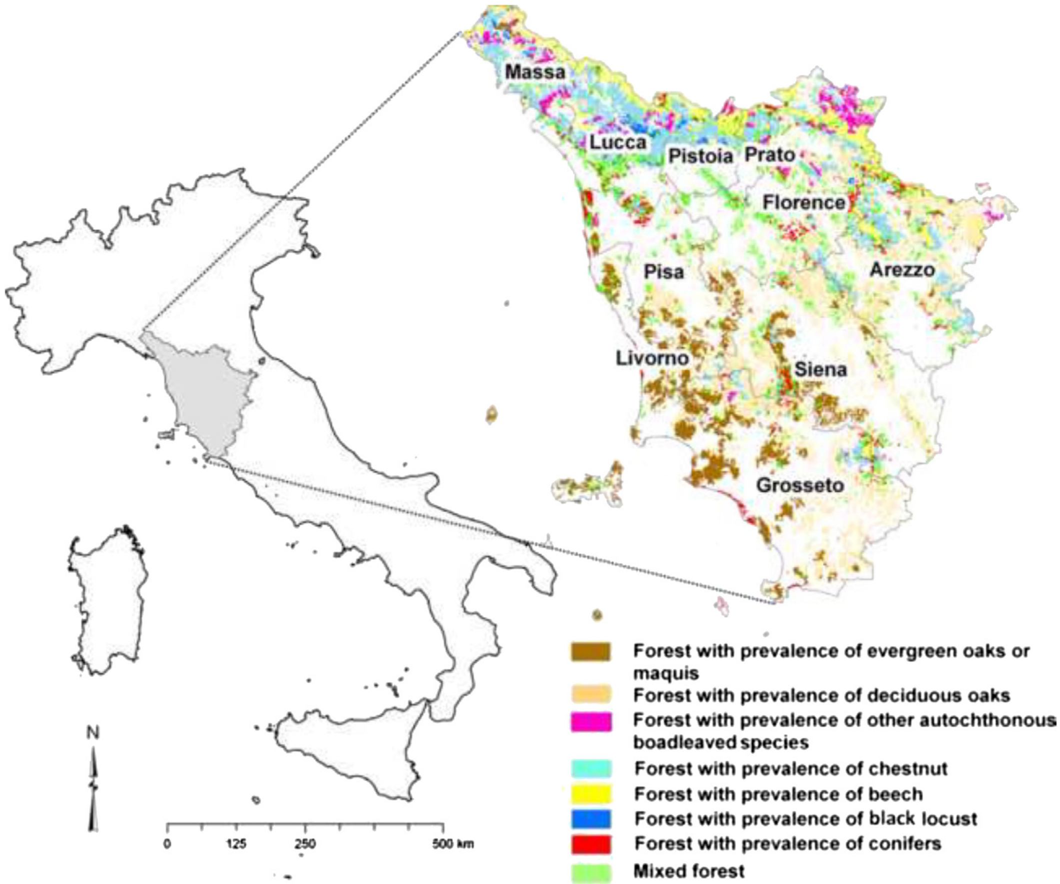

Fig. 1 – Study area localisation and forest typology (based on Corine Land Cover 2006).

Biomass availability was estimated according to the relationship between different input data, i.e., Tuscany Forest Inventory (TFI) and Corine Land Cover (CLC2006) [23].

The TFI is a sample-based inventory that includes both tree and plot level data. It is based on 400 m square grids sampled throughout the region. The TFI includes primary and secondary forest species, dendrometric characteristics, periodic annual increment and forest management. For each forest typology, the assorted mix applied in the region according to traditional practices was identified. This information was defined based on an analysis of the literature [24] and [25] by direct observations of forest processes and by interviews of local forest stakeholders.

Although the layers of CLC2006 represent the most available up-to-date forest map at the regional level, they do not report productivity for each forest typology. Therefore, the preliminary step of elaboration was to carry out a map overlay operation between CLC and TFI.

Periodic annual increment and partitions of assortments were calculated for each CLC polygon through a series of spatial summarizing operations based on TFI data and municipality localisation (Eq. (1) and Eq. (2)).

$$x_{CLCi,c,m} = \frac{\sum_{k=1}^{n_{q,m}} x_{TFIq}}{n_{q,m}} \Leftrightarrow \exists n_{q,m} \wedge \forall q \cong c \quad (1)$$

where $x_{CLCi,c,m}$ is the periodic annual increment for the *i-th* CLC polygon of *c-th* forest typology in *m-th* municipality, x_{TFIq} is the periodic annual increment for TFI point of *q-th* TFI forest typology, and $n_{q,m}$ is the number of TFI points of *q-th* TFI forest typology in *m-th* municipality.

$$P_{aCLCi,c,m} = \frac{\sum_{k=1}^{n_{q,m}} P_{aIFTq}}{n_{q,m}} \Leftrightarrow \exists n_{q,m} \wedge \forall q \cong c \quad (2)$$

where $P_{aCLCi,c,m}$ is the percentage of *a-th* assortment for *i-th* CLC polygon of *c-th* forest typology in *m-th* municipality and P_{aTFIq} is the percentage of the *a-th* assortment for TFI point of *q-th* TFI forest typology.

Periodic annual increment was associated with soil fertility to establish management typology in broadleaved forests where TFI forest management data are not available [24].

The second step in the ecological biomass availability estimation was the definition of annual yield.

A typical and widespread forest treatment for Tuscany coppices and high forests is area-wise felling. This indicates that a generic area A can be sub-divided into N sub-areas of surface S equal to A N^{-1} for these forests. With a long-term approach, this indicates that a property can be structured to have N forest stands with the identical surface area and an increasing age from 0 to the rotation period R_p.

The yield will depend on the stock growing in each forest stand and on the rotation period of each forest typology (Eq. (3)):

$$Y_c = \int_0^{Rp} g_c \cdot t^{-1} dt \quad (3)$$

where Y_c is the total annual yield for *c-th* forest typology, R_p is the rotation period for *c-th* forest typology, and g_c is the growing stock of biomass for *c-th* forest typology at time t.

Equation (3) can be modified as follows:

$$Y_c = \int_0^{Rp} x_{CLCi,c,m} \cdot t \cdot t^{-1} dt = \int_0^{Rp} x_{CLCi,c,m} dt \tag{4}$$

The choice of rotation period R_p is thus necessary to compute the annual yield for each forest typology. Over the long term, it was assessed as the period that maximises net revenues F according to the Faustmann formula [26] and [27] (Eq. (5)):

$$\max F \rightarrow \max \frac{Z_{Rp} + \sum Z_w \cdot q^{Rp-w} - T \cdot q^{Rp}}{q^{Rp} - 1} + \frac{J - B}{r} \quad \text{s.t.} \quad R_p \in \text{rotation period permitted by forest policy and regulations} \tag{5}$$

where Z_{Rp} is the net stumpage value of the final felling (the difference between total revenues from traditional assortments selling and energy-biomass selling and the total costs of silvicultural operations), Z_w is the net stumpage value of intermediate cutting at year w, T is the regeneration cost at rotation age R_p, q is $1 + r$ (where r is the discount rate), J is annual revenues, and B represents annual expenses.

Finally, the ecological biomass availability, $Y_{R,c}$, will depend on the total annual yield (Eq. (6)). Thus, wood-energy assortments (firewood and woodchips) can be quantified as a percentage of total annual yield, in accordance with Eq. (2) and scenario assessment [24].

$$Y_{R,c} = f\left(\int_0^{Rp} x_{CLCi,c,m} dt\right) \tag{6}$$

2.3.2. *Economic biomass availability*

The economic biomass availability was calculated as the ecological availability of the forest when the amount available after subtracting the total costs of silvicultural operations from the total revenues from traditional assortments selling and energy-biomass selling is positive. Thus, the biomass of areas with positive net stumpage value was considered.

In this phase, the model introduces processing constraints, such as geomorphological and technical limitations [28]. The modelling of harvesting systems and the entire energy chain was based on the slope, the distance of the forest from the main and forest roads, the distance from the municipality county seat, forest management and the development scenario. The absence of a suitable soil roughness database and a landing site localisation in the study area prohibits us from utilizing these parameters in the analysis.

Felling operations were performed by a forestry worker with chainsaw. The extraction typology depends on the slope and the distance from the road (Fig. 2), and based on the presence/absence of natural obstacles (rivers, lakes, ridges and peaks) defined through a Topographic Position Index operation [29] on the DTM.

Cable crane extraction was evaluated using mobile tower machinery with different power usages (low power in coppices and medium-high power in high forests). Ground-based extraction was calculated by utilizing a tractor and winch.

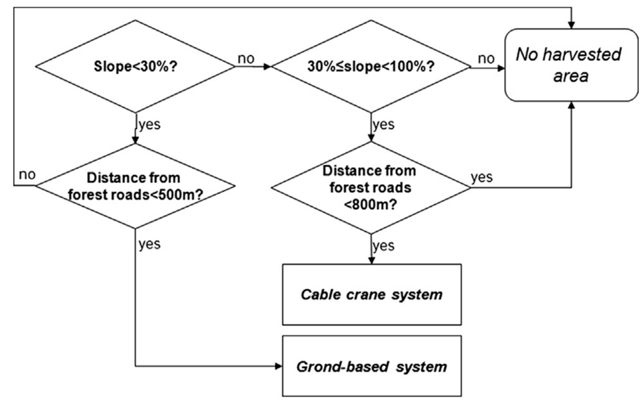

Fig. 2 – Extraction system.

Roundwood and other assortments were sold at landing, according to traditional practise. Firewood and woodchips were delivered to final users in the municipality county seat; this simplification results from the widespread firewood market, a long-term approach, the hypothesis of potentially increasing the number of District Heating Plants and the implementation of biomass logistic and trade centres [30] for the storage and processing of wood-energy. Transportation is differentiated by the distance from the forest roads to the municipality county seat; a machine cost analysis highlighted that the tractor and trailer combination is efficient up to a range of transportation of 8 km, but truck-based transportation was more efficient over this distance. Extraction and transport distance computation were performed utilizing a spatial *cost surface* operation [31].

The productivity of each processing phase relies on the morphological characteristics of the trees, tree diameter and tree volume (for felling operation), tree size (for processing), the volume harvested (for chipping) and the volume harvested and extraction/transport distance (for extraction and transport operations); delay times were also computed. The unitary productivity value refers to [32], [33], [34], [35], and [36] (see Table A.1 in Appendix). Table A.1 highlights the number of workers, worker skill level and hourly cost (from the collective agreement for national forestry workers) and machines used in different processes. Machine hourly costs were calculated utilizing Miyata methodologies [37].

For every *v-th* process phase and *j-th* forest pixel, processing costs K_P were calculated as shown in (Eq. (7)):

$$K_{P,v,j} = \frac{k_{h,v,j}}{p_{v,j}} \cdot Y_j \tag{7}$$

where $k_{h,v,j}$ is the hourly cost for *v-th* process phase in *j-th* forest pixel, $p_{v,j}$ is the productivity for *v-th* process phase in *j-th* forest pixel, and Y_j represents yield for *j-th* forest pixel (expressed as traditional assortments and/or residues).

Direction expenses, D_j, administrative cost, Ad_j, and interest, I_j, were also calculated [36] to define total cost $K_{T,j}$ (Eq. (8)).

$$K_{T,j} = K_{P,v,j} + D_j + Ad_j + I_j \tag{8}$$

Total revenues were then estimated. The model considers that more than one wood assortment can be produced in a

Table 1 – Results for scenario 2 and scenario 3.

Assortment	Woodchip price (€ t^{-1})							
	20	40	60	80	100	120	140	160
Firewood (SC2) (Mt $year^{-1}$)	0.97	0.99	1.00	1.01	1.01	1.02	1.03	1.03
Woodchips (SC2) (Mt $year^{-1}$)	0.43	0.44	0.45	0.45	0.46	0.46	0.47	0.47
Net revenues (SC2) (M€ $year^{-1}$)	68.3	76.3	84.5	92.8	101	110	118	127
Woodchips (SC3) (Mt $year^{-1}$)	0.38	0.89	1.29	1.41	1.47	1.50	1.52	1.54
Net revenues (SC3) (M€ $year^{-1}$)	22.3	32.5	53.3	78.4	105	132	160	188

single forest stand. Actual selling prices of woody materials were defined by specialised review and compared with information provided by forest owners and technicians.

Formally, the revenues Z obtained from the *j-th* pixel are (Eq. (9)):

$$Z_j = \sum_{a=1}^{u} \left(Y_j \cdot P_{aCLCi,c,m} \cdot z_a \right) \tag{9}$$

where u is the number of a assortments in pixel j, Y_j is the total annual yield in pixel j, and z_a is the market price for the *a-th* assortment.

Finally, annual regional economic biomass availability $Econ_b$ is expressed by equation (10):

$$Econ_b = \sum_{j=1}^{h} Y_{R,c,j} \, \forall j \in \left(Z_j - K_{T,j} > 0 \right) \tag{10}$$

where h is the total number of forest pixels in the Tuscany region.

3. Results and discussion

3.1. *Ecological biomass availability*

Sustainable wood-energy extraction was identified as the maximum rate of firewood and woodchips obtainable from the Tuscany forest that is lower than or equal to the annual increment for each forest typology. The total woodchip amount refers to the final felling residuals and non-commercial material from thinning interventions. Values were reported in tonnes per year (moisture content: 40%), as per widespread local market practices.

The results highlight that ecological biomass availability comprises 1.65 Mt $year^{-1}$ of firewood and 0.77 Mt $yeasr^{-1}$ of woodchips. The introduction of economic parameters reduces these values, as shown in the following paragraph.

3.2. *Economic biomass availability and scenario analysis*

SC1 quantifies the traditional energy assortment (firewood) and net revenues from the entire local forest chain according to current forestry practices and wood prices. Firewood amounts to 0.94 Mt $year^{-1}$ and total net revenues are 63.2 M€ $year^{-1}$ (net revenue for firewood amounts to 49.1 M€ $year^{-1}$).

The forest chain analysis highlights the importance of firewood in the current regional forest market. Unless firewood volume reaches 57% of the total potential yield, net revenues from forestry products used for firewood production are approximately 78% of the total economic value (accounting for the selling of roundwood, timber pole, etc.).

In SC2, the woodchips chain was introduced. SC3 provides a framework on the WTC system for firewood production areas. Sensitivity analysis depends on fluctuations in the price of woodchips. The results of the new hypotheses are explained in Table 1.

The introduction of complementary assortments (residues) into the production mix increases the economic advantages of forestry processes in SC2 when compared to SC1, as verified by firewood quantity and by the economic viewpoint. The WTC system makes SC3 more efficient than SC1 over 22.80 € t^{-1} for energy biomass availability and over 68.90 € t^{-1} in economic parameters.

The comparison between SC2 and SC3 depicts the Break Even Price (BEP) that switches the economic advantages from residues production to the WTC system (Fig. 3).

Biomass availability and net revenues become more efficient in SC3 compared to SC2 over the threshold of approximately 100 and 97 € t^{-1}, respectively. In SC2, total

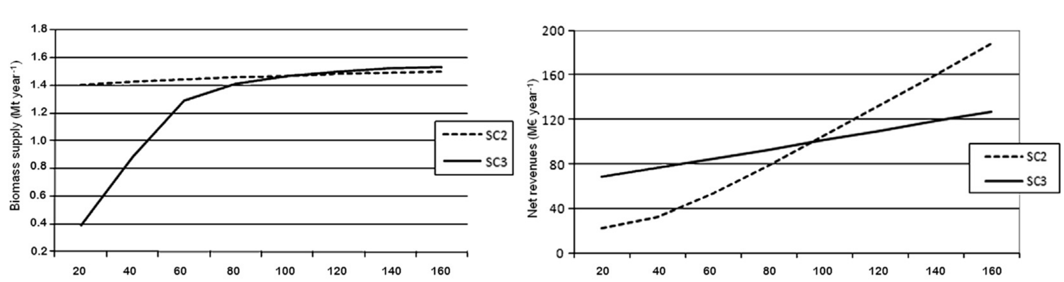

Fig. 3 – Cumulative biomass supply (t $year^{-1}$: M40) (left) and net revenues (M€ $year^{-1}$) (right) in SC2 and SC3, based on woodchips price (firewood price: 115 € t^{-1}).

Table 2 – Results for scenario 2 and scenario 3 (values for firewood production forests).

Assortment	Woodchip price (€ t^{-1})							
	20	40	60	80	100	120	140	160
Firewood (SC2) (Mt $year^{-1}$)	0.93	0.95	0.97	0.98	0.99	1.01	1.01	1.02
Woodchips (SC2) (Mt $year^{-1}$)	0.30	0.31	0.32	0.32	0.33	0.34	0.34	0.34
Net revenues (SC2) (M€ $year^{-1}$)	45.8	51.3	57.0	62.9	68.9	75.1	81.3	87.6
Woodchips (SC3) (Mt $year^{-1}$)	0.17	0.68	1.11	1.26	1.33	1.37	1.39	1.41
Net revenues (SC3) (M€ $year^{-1}$)	0.50	7.10	24.2	46.1	70.0	94.8	120	146

biomass is the sum of firewood and residues. These results strictly depend on forest characteristics and logistical parameters. As previously mentioned, the model outputs consider a fixed price of firewood and increasing prices for woodchips. In real market conditions, mechanisms that lead to a linked modification of these values may occur.

With this background, it is interesting to proceed with more detailed analyses for firewood production forests only. New values are shown in Table 2.

In SC2, the comparison between Table 1 and Table 2 (from total forest to only firewood production forests) highlights a reduction in the availability of woodchips in the range of 31–34%, although SC1 shows that firewood production is important for regional forest processes (only 22% of total net revenues are not attributable to firewood). In addition, a reduction in total net revenues in the range of 26–32% is also shown. These results indicate the increased importance of woodchip production for high forests.

Table 2 stresses how BEPs from SC2 to SC3 are 100 and 99 € t^{-1} for "biomass availability" and "net revenues", respectively. When the woodchip price range is 20–40 € t^{-1}, net revenues decrease approximately 33% in SC2 and 78–98% in SC3, with respect to the total forest analysis. The results show that innovative forest chains decrease economic efficiency when there are low prices for energy residues because of higher investment costs compared to the mechanisation level.

Fig. 4 defines the trade-off at the geographic level. In this case, the comparison depends on economic efficiency. With a fixed firewood price and increasing woodchip price, SC3 could become more convenient than SC2 and vice versa. If wood-energy prices change proportionally, the model shows efficiency for each local area (Fig. 5).

Fluctuations in the assortments price (+50% in the example of Fig. 5) leads to an increase of 97,131 ha of total surfaces with positive net stumpage value for SC2. The SC3 application decreases the previous value of 59,004 ha. This output indicates that the main wood assortments are more important in the trade-off definition and it confirms the results of research studies that have been conducted in Tuscany for different forest chains (timber pole production or WTC in chestnut forest [38]). The above concept was confirmed by an elasticity analysis of firewood and woodchip prices, with elasticity defined as a measure of responsiveness [39]; elasticity computes the change in variable *A* in response to a change of variable *B*. In Eq. (11), elasticity E_a is calculated as the percentage variation of the *a-th* assortment quantity based on the percentage variation of the *z-th* assortment price:

$$E_a = \frac{\Delta Q_a / Q_a}{\Delta z_z / z_z} = \frac{\Delta Q_a}{\Delta z_z} \cdot \frac{z_z}{Q_a} \tag{11}$$

where ΔQ_a is the variation in *a-th* assortment quantity, Q_a is the initial *a-th* assortment quantity, Δz_z is the variation in *z-th* assortment price, and Q_z is the initial *z-th* assortment price.

Elasticity of supply curves is shown in Fig. 6.

In SC2, the firewood price parameterisation shows that the firewood and woodchip supply curves are always inelastic ($E_a < 1$) when prices for residues are greater than 97.50 € t^{-1}. Woodchip pricing set to 65 and 32.50 € t^{-1} makes the curve elastic ($E_a > 1$) until the firewood price is 80 and 100 € t^{-1}, respectively.

Woodchip price parameterisation maintains an inelastic supply. This parameterisation in SC3 verifies the elastic range of the biomass supply under 64 € t^{-1} (approximate current mean market price).

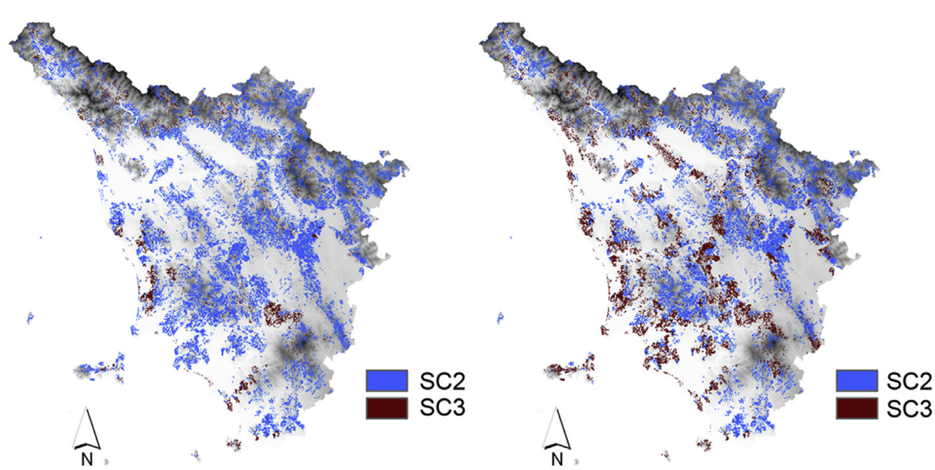

Fig. 4 – SC2 and SC3 trade-off. Firewood price: 115 € t^{-1}. Woodchip price: 60 € t^{-1} (left) e 100 € t^{-1} (right).

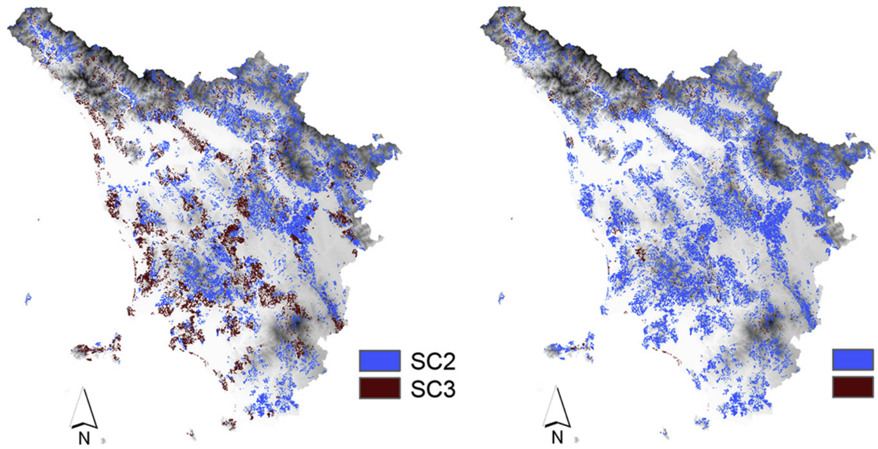

Fig. 5 – SC2 and SC3 trade-off. Left: Firewood price: 115 € t^{-1}. Woodchip price: 65 € t^{-1}. Right: Firewood price: 164 € t^{-1}. Woodchip price: 93 € t^{-1}.

These results outline the economic relevance of firewood with respect to woodchips in the regional market and shows that the implementation of SC3 depends primarily on the firewood price increment.

Finally, an analysis was undertaken to verify potential control variables in the scenario for efficiency measures. Therefore, a new spatial processing for data extraction at the forest typology level was undertaken. The forest typology

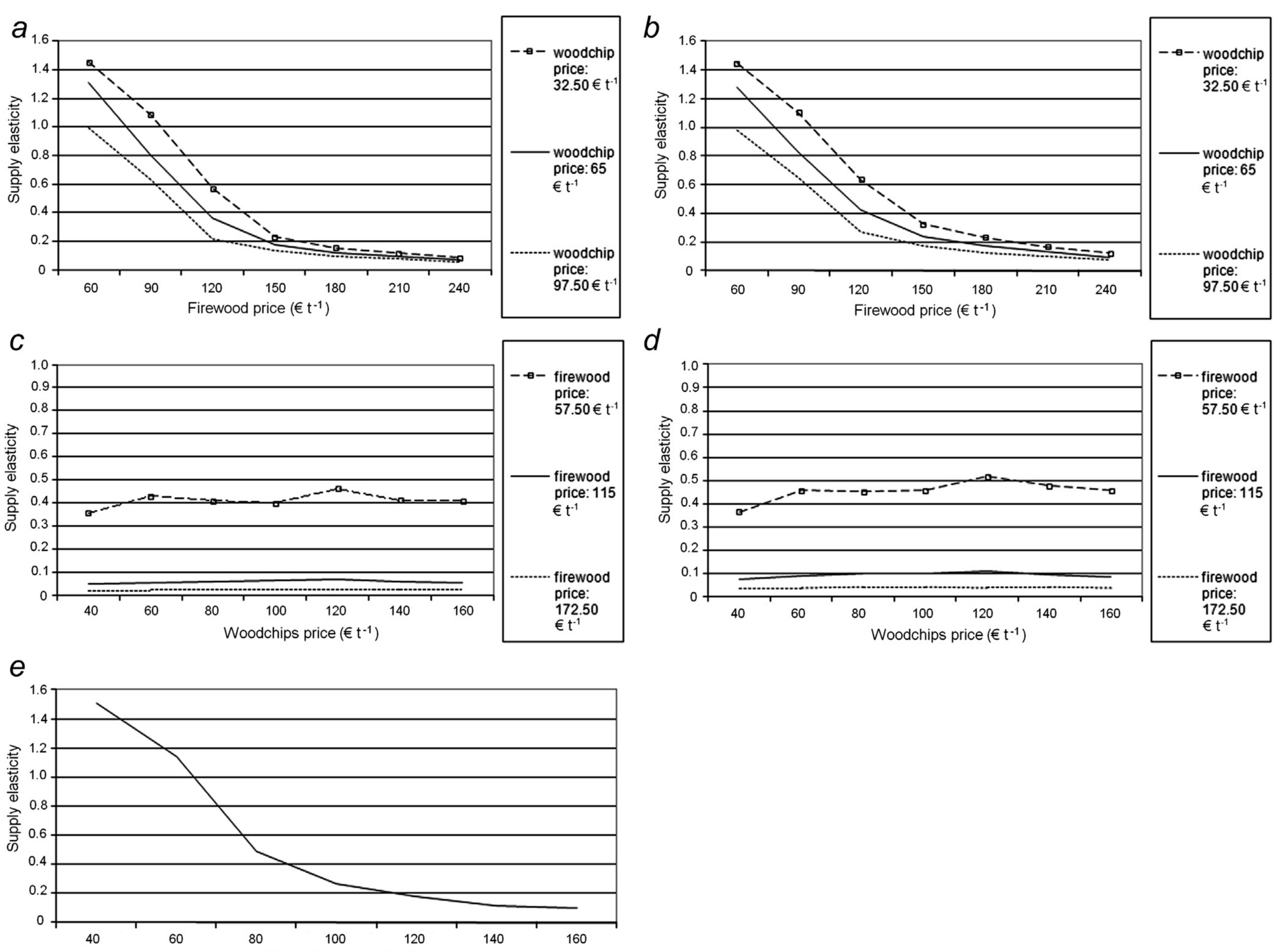

Fig. 6 – Elasticity of supply curves. Firewood elasticity (Figs. a and c) and woodchip elasticity (Figs. b, d and e) based on firewood price (Figs. a and b) and woodchip price (Figs. c, d and e) parameterisation. Figure e refers to SC3.

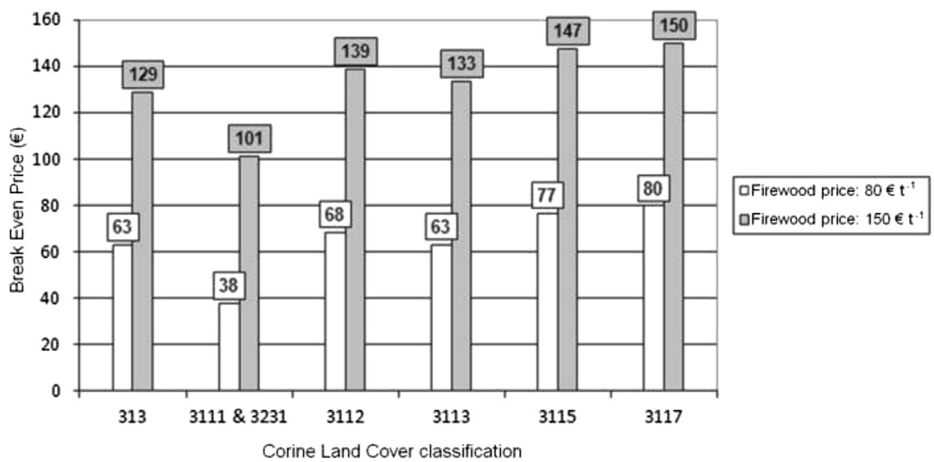

Fig. 7 – Woodchip break even price from SC2 to SC3 based on CLC classification.

considered includes the following surfaces where firewood is currently produced (as single assortments or in mix production):

- mixed forest (CLC code 313);
- forest with a prevalence of evergreen oaks or Mediterranean vegetation (high *maquis*) (CLC code: 3111 and 3231);
- forest with a prevalence of deciduous oaks (CLC code: 3112);
- forest with a prevalence of other autochthonous broadleaved species (CLC code: 3113);
- forest with a prevalence of beech (CLC code: 3115); and
- forest with a prevalence of black locust – *Robinia pseudoacacia* L. (CLC code: 3117).

Woodchip BEPs from SC2 to SC3 were calculated for each category, taking into account a woodchip price parameterisation and firewood price in the range of 80–150 € t^{-1}. The results are shown in Fig. 7.

The WTC system seems to be more efficient in forests with Mediterranean vegetation (evergreen oaks and *maquis*). This is most likely because the exclusion of delimbing and crosscutting operations is more economically efficient in low fertility soil that is characterised by trees with smaller volume. In these areas, processing phases are time consuming in comparison to the entire operation. With an increasing firewood price, the BEP increases from SC2 to SC3. A higher BEP increment was again observed for Mediterranean vegetation; in this case, the lower costs related to the WTC system are partially compensated for by the higher unitary value of firewood – and higher revenues from it – when mass density is the reference.

However, greater BEPs are reached for black locust and beech forests, with firewood prices of both 80 € t^{-1} and 150 € t^{-1}. In these forest stands, the widespread medium-high fertility generally increases tree volume and facilitates processing operations. Intermediate BEP values are presented for oaks, other broadleaved trees and mixed forests.

4. Conclusions

The spatial analysis model developed in this paper permits us to quantify biomass availability in forest stands in accordance with ecological and economic parameters. Different production chain organisations were evaluated both with traditional mechanisation levels and with hypothesised innovative production processes. The trade-off scenario outlines how an integrated harvesting system is an efficient methodology for biomass amount and from an economic point of view. In firewood production forests, a WTC system can be affected by economic and vegetation variables, and local analysis is necessary for its implementation. The results confirm what Manley and Richardson [19] stated: "*Among possible directions biomass for energy production might take, it is conceivable that hardwood coppices with clearcutting would be present but not on a large scale. Optimal usage of the available products, especially wood for energy, would be preferable*". However, the geographic-based model appears to be the proper support to analyse the guideline schematics in this framework. The results were estimated in a multiscale approach based on administrative boundaries and territorial peculiarities. Some applications of the tool would be to estimate biomass availability and to apply agro-forestry funds in administrative areas more suitable for energy chain activation/implementation. To pursue these goals and to make the tool fit for operational use, an estimate of the biomass demand/supply ratio must be conducted and an analysis of current bioenergy market trends at the local level must be undertaken. Additional improvements may be related to the implementation of up-to-date logistical layers (forest roads characteristics, landing sites localisation, etc.) and to the analysis of the current local wood-energy chain organisation. Up-to-date logistical layers seem to be important parameters in the analysis, particularly for biomass supply quantification. These variables may be difficult to be introduced because additional large-scale forest surveys are required. In future analyses, additional forest-oriented parameters may be identified in the spatial evaluation and results, such as relationships among biomass production and traditional assortments (e.g. roundwood), site quality indices, yield classes and specific coppice rotations. In the assessment of the economic analysis, loss of material should also be included, particularly for chipping.

Finally, field mechanisation experiments in forest stands may confirm trade-off scenario from integrated harvesting to

WTC system in specific firewood production coppices. In these studies, the mechanisation parameters and environmental effects of the residue chain must be analysed, in addition to the economic aspects.

The above-mentioned improvements may obtain a suitable tool for operational use in a Decision Support process for the bioenergy sector. In particular, such a tool may be useful for policy makers at medium-high administrative level (provincial, regional, etc.).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2012.11.026.

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