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ORIGINAL PAPER

A geography-based decision support tool to quantify the circular bioeconomy and financial performance in the forest-based sector (r.forcircular)

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Abstract

This study focuses on the development, implementation and application of a spatial-based decision support tool—named r.forcircular—aimed at quantifying both the level of the circular bioeconomy and the financial performance in the forest-based sector. The methodology merges a set of indicators based on the 4R framework (Reduce, Reuse, Recycle, Recover) of circular economy in a multicriteria approach. Outputs are computed for different scenarios and are calibrated based on variations in the selling price of raw materials and on higher mechanisation of production process phases (felling, processing, extraction and chipping of wood residues). The increase in wood assortment value leads to an improvement in the sustainability of the forest-wood supply chain in circular bioeconomy and financial terms. The application of a higher level of mechanisation seems to have conflicting results compared to those of other scenarios. The r.forcircular model was tested in an Italian case study (in the Municipality Union of Valdarno and Valdisieve in the Tuscany region, Italy) with the aim of understanding its applicability and replicability in other contexts. The results of the test showed that, in the study area, superior outcomes were observed for high forests than for coppices due to the low value of wood products obtainable from coppices.

Keywords Forest-wood supply chain · Provisioning services · Sustainability · Spatial analysis · Multicriteria evaluation

Introduction

In recent decades, the growing anthropogenic pressure on the environment has forced the international policy community to adopt strategies and policies to reduce the negative impacts on natural resources (Markard et al. 2012). In this context, the traditional linear economy paradigm has been challenged by a more sustainable paradigm—known as the circular economy or circular bioeconomy paradigm—aimed at reducing the use of fossil fuels, the production of waste and the impacts on natural resources (Bruhn et al. 2016; Loiseau et al. 2016).

The European Bioeconomy Strategy (European Commission 2018) pays particular attention to the concept of a circular bioeconomy merging the themes of "circular economy" and "bioeconomy". On the one hand, the circular economy aims at the minimisation of input and waste by promoting the application of the 4R framework (Reduce, Reuse, Recycle, Recover) throughout production processes and the provision of services (Kirchherr et al. 2017; Toppinen et al. 2020). On the other hand, the bioeconomy promotes the substitution or complementation of industrial inputs with renewable biological resources (Bugge et al. 2016; Toppinen et al. 2020). The combination of the two concepts allows us to cope with the limitations of both the circular economy and bioeconomy as well as to improve political discussion about their role in sustainable development (Hetemäki 2017). In

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fact, although the themes of both the circular economy and bioeconomy have been largely explored in environmental analysis, albeit with alternative terms and definitions (Toppinen et al. 2020), the introduction of the new term "circular bioeconomy" facilitates the categorisation of the subject, which promotes political strategies, the depiction of targets and the attainment of goals.

Forest resources play a key role in this sense, with relevant reference to the cascading principle (Mair and Stern 2017), the potential of bioenergy production (Pieratti et al. 2019) and the minimisation of negative trade-offs among ecosystem services (Bais-Moleman et al. 2018). As emphasised by the New EU Forest Strategy for 2030, the circular bioeconomy is an important opportunity to connect socio-economic and technical processes with environmental sustainability in the forest-wood supply chain (European Commission 2021). However, circular economy and bioeconomy have rarely been analysed in the same framework in forest research (Weiss et al. 2021). Interest in the above-mentioned issues has rapidly increased in both the scientific and the grey literature, but some authors stress how the two can be represented as evolving concepts in the forest-based sector (Biancolillo et al. 2020).

Forest-based circular bioeconomy and its relationship with sustainability challenges and novel business opportunities were investigated in a Special Issue of Forest Policy and Economics, "Forest-based circular bioeconomy: matching sustainability challenges and new business opportunities", edited by Anne Toppinen, Tobias Stern and Dalia D'Amato. In the Special Issue, the macro-categories of discourse and governance, industry and business and biorefineries as an innovation platform were investigated (Toppinen et al. 2020). A few additional studies on the circular bioeconomy applied to forests are available in the scientific literature. Of these, the majority focus on literature reviews debating the impact of deadwood conservation in public forests (Chisika et al. 2021), the definition of commercially viable products (Brandão et al. 2021), biomass and bioresidual availability in forest areas (Kumar et al. 2021; Gregg et al. 2020) or the innovative application of wood products (Baldwin 2020; Wenger et al. 2020). Other studies investigate novel business or socio-technical models important for the transition to a circular bioeconomy in the forest-based sector (Näyhä 2021; Hansen et al. 2021).

The novelty of the topic highlights how a few methods have been applied to guide decision and policy-makers in the application and quantification of circularity in the forest-based sector. By means of material flow analysis and a set of indicators, Gonçalves et al. (2021) analysed forest biomass flows and stocks in Portugal to quantify circularity and resource efficiency. Linser and Lier (2020) focused on how different countries have applied indicators to compute circular bioeconomies in national strategies and their relationship with the 2030 Sustainable Development Goals (SDGs) of the United Nations. A resilience strategic framework was applied by Sanz-Hernández (2021) for marginalised forested areas of Spain through a qualitative analysis to facilitate promotion strategies grounded in a circular bioeconomy. D'Amato et al. (2020) employed questionnaires and interviews gathered from managers in Finnish forest SME companies to outline the main characteristics of business models and stakeholders involved in circular bioeconomy applications.

To the best of the present authors' knowledge, specific models, tools or decision support systems (DSSs) to quantify the level of circular bioeconomy in a specific forest-wood supply chain currently do not exist.

The main objective of this work is to describe the development and application of a DSS—named r.forcircular—aimed at analysing and measuring the level of sustainability of a forest-wood supply chain in the context of a circular bioeconomy. The rest of the paper is organised as follows: in the "Material and methods" section, the general framework, applied methodologies and the structure of the model are described; in the "Results" section, the main findings of DSS and output from the scenario analysis are reported; the last sections offer discussion and indication of knowledge gaps as well as some conclusions.

Material and methods

General framework

The model (r.forcircular) is implemented as an add-on to the more recent stable releases GRASS GIS 7.8 and 8. It is currently available both with a graphical user interface (integrated as GRASS GIS extension) and in bash script format. The DSS can be considered the first spatial-based tool to facilitate circular bioeconomy quantification in the forest-based sector to practically address forest policy and planning goals. The DSS allows for importing vector and raster geographical data and for setting parameters related to the study area boundaries, geomorphology, forest stand characteristics, as well as technical and economic variables. The model identifies forest areas potentially exploitable from both technical (based on geomorphological, logistic and mechanisation variables) and economic (through the estimation of stumpage value) perspectives. Subsequently, the use of indicators belonging to the 4R framework of the circular economy (Reduce, Reuse, Recycle, Recover) allows for evaluating the level of circularity of the forest-wood supply chain. Finally, the application of spatial multicriteria analysis (SMCA) (specifically with the compromise programming—CP—technique) permits the merging of a unique measure of the level of circular bioeconomy for the production of traditional wood assortments and bioenergy in forest areas. In the SMCA procedure, each indicator is weighted according to an online questionnaire proposed to decision-makers operating in the forest-based sector.

Structure of the model

The land information system (LIS) is composed of all geodata needed to run the model. Specifically, they can be divided into mandatory or optional files as shown in Table 1.

Table 2 shows the nomenclature used in the present paper.

Quantification of technical and financial availability of biomass

The quantification of circular bioeconomy indicators was developed in the framework of provisioning forest ecosystem services (production of raw material; Millennium Ecosystem Assessment 2005). For this reason, the indicators and results of the SMCA process were computed on the forest surface with financial efficiency of the production process or, in other words, the area where a positive stumpage value can be reached. The calculation of the stumpage value was carried out following the approach of another GRASS GIS add-on: r.green.biomassfor (Sacchelli et al. 2013a). The model starts with the importation of geodata and the conversion of vectors to rasters. Next, through a multistep approach,

Table 1 Land Information System

Geodata	Description or unit of measure	Mandatory (M)/optional (O)	Geodata	Description or unit of measure	Mandatory (M) / optional (O)
Tracks	Vectorial file reporting forest roads	M	Soil productivity or fertility*	From very low (value 1 in the attribute table) to very high (value 5 in the attribute table)	O
Boundaries	Vectorial file representing the boundary of study area	O	Rotation period*	years	M
Digital Terrain Model (DTM)	Altitude (m a.s.l.)	M	Percentage of harvested trees during silvicultural intervention (final harvesting or intermediate thinning)*	%	M
Annual average increment*	$m^3/ha \cdot y^{-1}$	M	Partitioning of increment in assortments*	% roundwood, % timber pole, % firewood, % residues for bioenergy production	M
Management*	High forest (value 1 in the attribute table) or coppice (value 2 in the attribute table)	M	Price of assortment*	€/m^3	M
Treatment*	Final harvesting (value 1 in in the attribute table) or intermediate intervention (e.g. thinning—value 2 in the attribute table)	M	Mean low calorific value of forest species or typologies (LCV)*	MWh/m^3	M
Roughness of terrain*	From absent (value 0 in the attribute table) to high (value 3 in the attribute table)	O	Rivers	Localisation of rivers	O
Mean tree diameter*	Cm	O	Lakes	Localisation of lakes	O
Mean tree volume*	m^3	O	Protected areas	Localisation of protected areas	O
Forest species or typologies*	Name of forest species or typologies	O			

*Column contained in the "forest map", a vectorial file representing polygons of forest compartments or homogeneous forest type and describing vegetational, soil and management characteristics

Table 2 Nomenclature

Symbol	Unit of measure	Description	Symbol	Unit of measure	Description
s	%	Slope of terrain	β	m^3	Volume of roundwood for furniture
$\overbrace{U_{s,g}}^{set}$	%	Upper limit of slope for ground-based (g) extraction (set by user)	γ	m^3	Volume of roundwood for building
d	m	Distance from forest road	δ	m^3	Volume of roundwood for other uses
$\overbrace{U_{d,g}}^{set}$	m	Upper limit of distance for ground-based (g) extraction (set by user)	$\%\alpha$	%	Percentage of roundwood for paper
h	From absent (0) to high (3)	Roughness of terrain	$\%\beta$	%	Percentage of roundwood for furniture
$\overbrace{U_{h,g}}^{set}$	From 0 to 3	Upper limit of roughness for ground-based (g) extraction (set by user)	$\%\gamma$	%	Percentage of roundwood for building
$\overbrace{U_{s,a}}^{set}$	%	Upper limit of slope for aerial-based (a) extraction (set by user)	$\%\delta$	%	Percentage of roundwood for other uses
$\overbrace{L_{s,a}}^{set}$	%	Lower limit of slope for aerial-based (a) extraction (set by user)	μ	–	Total number of cycles for reuse of a specific assortments
$\overbrace{U_{d,a}}^{set}$	m	Upper limit of distance for aerial-based (a) extraction (set by user)	θ	%	Percentage of reuse of the product in every cycle
ω	$m^3/ha \cdot y^{-1}$	Annual average increment	χ	y	Lifespan of product
x	%	Partitioning of increment in assortments (see Eqs. 6–12)	LCV	MWh/m^3	Low calorific value of f specie or group of species
f	–	Forest species or typologies	ρ	tCO_2/MWh	Conversion factor from produced bioenergy to avoided CO_2 emission due to alternative use of fossil fuel in heating plants (Francescato and Antonini 2010)
m	–	Forest management (high forest or coppice)	λ	MWh	Bioenergy ($\lambda = c \cdot LCV$)
R	y	Rotation period	ϕSV	€/y	Annual stumpage value
H	%	Percentage of harvested trees in final harvesting or intermediate thinning	$\overline{\phi SV}$	$€/ha \bullet y^{-1}$	Average annual stumpage value
p	$€/m^3$	Price of assortment	SV	€/ha	Average stumpage value at harvesting
o	–	Phase of production process	AE	tCO_2/y	Annual avoided emission of CO_2
u	€/h	Hourly unitary cost for the o phase	DIP	Adimensional	Distance from ideal point
η	m^3/h	Efficiency of the o phase	n	–	Scenario
e	€/ha	General expenses	i	See indicator	Indicator of circular bioeconomy
r	%	Interest rate	I	–	Number of indicators of circular bioeconomy
$\sum_o CO_2$	tCO_2	Total carbon dioxide emission in forest production process	τ	Adimensional	Weight of i indicator
F	ha	Forest surface	v^+	See indicator	Ideal value of i indicator
t	m^3	Volume of timber pole	v^-	See indicator	Anti-ideal value of i indicator
w	m^3	Volume of firewood	v	See indicator	Value of i indicator in n scenario
c	m^3	Volume of woodchips	ε	Adimensional	Metric applied in CP model
α	m^3	Volume of roundwood for paper	q	–	$1 + r$
σ	–	Cycle of reuse for wood assortments in the range from 1 to μ			

the technical and economic availability of biomass (both traditional wood assortments and woodchips for bioenergy production) were quantified. Technical availability depicts the forest surface where the extraction of wood material is possible. This approach combines the type of mechanisation, limits for slope, distance from roads and roughness (Sacchelli et al. 2013a). In DSS r.forcircular, the user can set the upper and, if needed, lower limits for slope and distance from roads (Eq. 1) as well as the extraction vehicle used in the case study (high- or medium–low-power cable crane, forwarder, skidder, tractor or other).

$$if\left[\left(\left(s \le \overbrace{U_{s,g}}^{\text{set}}\right) \wedge \left(d \le \overbrace{U_{d,g}}^{\text{set}}\right) \wedge \left(h \le \overbrace{U_{h,g}}^{\text{set}}\right) IS\ THRUE\ then\ GROUND\ BASED\ EXTRACTION\right] else \atop if\left[\left(\left(s \le \overbrace{U_{s,a}}^{\text{set}} \wedge s > \overbrace{L_{s,a}}^{\text{set}}\right) \wedge \left(d \le \overbrace{U_{d,a}}^{\text{set}}\right) IS\ THRUE\ then\ AERIAL\ BASED\ EXTRACTION\right] else \atop biomass\ not\ available \tag{1}$$

In forest areas where extraction was possible, the stumpage value was quantified according to Eq. 2:

$$SV = \left[\left(\omega_{x,f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot p_x\right) - \left(\omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \frac{u_o}{\eta_o} + e\right)\right] \forall x \in f \tag{2}$$

The phases of the production process are felling and/or felling-processing, processing, extraction and chipping of wood residues. The hourly unitary cost included the machine and worker costs and can be set by the user. Hourly productivity was automatically quantified based on slope, tree characteristics, prescribed yield and extraction distance (Sacchelli et al. 2013a). Delay times were also computed. General expenses (e) were composed of managerial costs for the organisation of the production process and administrative costs due to bureaucracy and interest; these were quantified according to the method proposed by Bernetti and Romano (2007).

Indicators of circular bioeconomy

In their recent work, Paletto et al. (2021) carried out a study focused on the application of.

circular bioeconomy in a forest-based sector. The research was structured in three steps: (1) a literature review on circular bioeconomy related to the forest-based sector by applying social network analysis to bibliometric science; (2) the identification of a set of indicators suitable to assess the forest-based sector; and (3) the identification of an order of priority of the circular bioeconomy indicators based on decision-makers' opinions. Starting from the results of that study, a set of indicators to describe and quantify the circular bioeconomy of the forest-wood supply chain was depicted. This list was then redefined to choose indicators applicable in spatial models. The indicators currently presented in the model are reported in Table 3.

Table 3 Indicators of circular bioeconomy applied in DSS r.forcircular

4R	Indicator	Definition
Reduce	*i*1—Ratio (on annual basis) between annual value and annual mean volume of harvested mass (€/m^3·y^{-1})	Improving of the process efficiency reducing the utilisation of natural resources
	*i*2—CO_2 emissions per unit of wood product (tCO_2/m^3)	
Reuse	*i*3—Harvested surface (ha/y)	Forest surface yearly harvested (surface with stumpage value greater than zero)
	*i*4—Index of reuse (m^3·years)	The index combines: (i) the wood products lifespan of product; (ii) the percentage of wood product/material that can be reused; and (iii) the number of cycles of wood product reuse
Recycle	*i*5—Ratio between the potential economic value of the wood assortment and the real value earned (€/€)	Valorisation of the valuable wood high-quality assortments. The indicator hypothesises that current value of wood assortments can be improved in alternative—and more remunerative—market (e.g. small branches applied for pizzeria or restaurant instead of woodchips etc.)
Recover	*i*6—Percentage of wood waste for bioenergy production (%)	Energy recovery from wood waste products. Wood waste is here intended as residuals from harvesting (e.g. tops, branches etc.)
	*i*7—Amount of CO_2 emissions saved per unit of energy produced by wood wastes (gCO_2/kWh)	Emissions saved from energy recovery from waste wood products

Modellisation of each indicator was performed as follows: I_1 is computed according to Eq. 3:

$$i1 = \frac{\mathrm{SV} \cdot \left(\frac{r}{q^{R-1}}\right)}{\omega \cdot H} \tag{3}$$

The CO_2 emissions per unit of produced assortments ($i2$) can be formalised as shown in Eq. 4:

$$i2 = \frac{\sum_o CO_2}{\omega \cdot H} \tag{4}$$

The CO_2 emissions for each phase of the production process ($\sum_o CO_2$) were computed using the procedure applied in Sacchelli et al. (2013a), which combines harvested material (m^3), the efficiency of each phase (m^3/h), fuel consumption of machinery (l fuel/h) and conversion factor (gCO_2/l fuel).

The annual harvested surface ($i3$) can be considered a proxy of material flow. It is quantified as the sum of forest surface yearly harvestable with financial efficiency (Eq. 5):

$$i3 = \sum \frac{F}{R} \forall F \quad \text{where} \quad \mathrm{SV} > 0 \tag{5}$$

DSS r.forcircular hypothesises four different assortments: roundwood, timber pole, firewood and woodchips. The model assumes a specific destination for the last three wood products quantified as in Eqs. 6–8:

$$t = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_t \tag{6}$$

$$w = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_w \tag{7}$$

$$c = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_c \tag{8}$$

Roundwood can be allocated in different forest-wood chains for different purposes; users can define the percentage of destination to paper, furniture, building or other uses to quantify each product (Eq. 9–12):

$$\alpha = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_\alpha \tag{9}$$

$$\beta = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_\beta \tag{10}$$

$$\gamma = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_\gamma \tag{11}$$

$$\delta = \omega_{f,m} \cdot R_{f,m} \cdot H_{f,m} \cdot \%_\delta \tag{12}$$

The additional indicator of reuse ($i4$) is composed of three different indices combined in a unique algorithm (Eq. 13): the lifespan of products, the potential reuse and the numbers of reuse cycles:

$$i4 = \alpha + \chi_\alpha \cdot \sum_{\sigma=1}^{\mu_\alpha} \alpha \cdot \theta_\alpha + \beta + \chi_\beta \cdot \sum_{\sigma=1}^{\mu_\beta} \beta \cdot \theta_\beta + \gamma + \chi_\gamma \cdot \sum_{\sigma=1}^{\mu_\gamma} \gamma \cdot \theta_\gamma + \delta + \chi_\delta \cdot \sum_{\sigma=1}^{\mu_\delta} \delta \cdot \theta_\delta + t + \chi_t \cdot \sum_{\sigma=1}^{\mu_t} t \cdot \theta_t + w + \chi_w \cdot \sum_{\sigma=1}^{\mu_w} w \cdot \theta_w + c + \chi_c \cdot \sum_{\sigma=1}^{\mu_c} c \cdot \theta_c \tag{13}$$

The ratio between the potential economic value of the wood assortment and the real value earned ($i5$) is an adimensional number that expresses the potential improvement of the forest-wood supply chain in economic terms. The improvement can be theoretically reached in different ways, for example, with alternative destinations of wood material and enhancement of selling prices. In r.forcircular, the improvement is obtained through an alternative partitioning of the increment $\omega_{x,f,m}$ among assortments. In practice, $i5$ compares the current use of wood with an optimised one selected by the user according to local peculiarities and the forest market. Indicator 5 is included in the "Recycle" group because recycling is here intended in general term as "the process of converting materials into new objects". Therefore, the wood assortments with the highest added value are those that can potentially be recycled as opposed to those with low added value (e.g. wood used for bioenergy production).

Indicator $i6$ quantifies the energy recovery from waste, identifying the percentage of woodchips produced in the study area.

The other recovery indicator ($i7$) reports the CO_2 emissions saved per unit of energy produced by woodchips through Eq. 14:

$$i7 = \frac{\left(c \cdot \mathrm{LCV} \cdot \rho - \sum_o CO_2\right) \cdot 10^6}{c \cdot \mathrm{LCV} \cdot 10^3} \tag{14}$$

Weighting of indicators

The importance of each circular bioeconomy indicator was derived from Paletto et al. (2021), in which—starting from a total sample of 56 decision-makers operating in the forest-based sector in Italy—30 decision-makers completed a questionnaire (11 representatives of public administrations, 11 representatives of private companies and 8 freelancers). The decision-makers involved in the study were identified based on their knowledge and experience in the fields of bioeconomy, circular economics and forest policy.

The questionnaire was composed—among other sections—by one question for each indicator asking the respondent to assess the indicator's weight considering three criteria (efficiency, applicability, replicability) and using a 5-point Likert scale format (from 1 = very low importance to 5 = very high importance). According to the outputs provided by Paletto et al. (2021), the results currently applied in r.forcircular (but modifiable by users) were $i1 = 0.15$, $i2 = 0.12$, $i3 = 0.12$, $i4 = 0.13$, $i5 = 0.14$, $i6 = 0.17$ and $i7 = 0.16$.

Reporting of results and spatial multicriteria analysis

The DSS highlights the output in both numerical and geographical formats. By means of zonal statistics operations, the following results can be reported for the forest surface where SV > 0: annual availability of assortments (m^3/y) recalibrated in the category of harvested material (i.e. roundwood, timber pole, firewood and woodchips converted into bioenergy and expressed as MWh/y), annual stumpage value (€/y), average annual stumpage value (€/ha·y^{-1}), average stumpage value at harvesting (€/ha) and avoided CO_2 emissions (tCO_2/y).

Quantification of the circular bioeconomy is expressed by an SMCA procedure based on the compromise programming (CP) technique (Carver 1991). CP depicts the distance from the so-called "ideal" point (Romero and Rehman 2003), a hypothetical alternative defined as the most suitable level for each indicator (i) in the considered scenario (n) (Malczewski 1999). The distance from the ideal point (DIP) is measured with the decision rule:

$$\mathrm{DIP}_n = \left\{ \sum_{i=1}^{I} \tau_i \cdot \frac{v_{i,n}^{+} - v_{i,n}}{v_{i,n}^{+} - v_{i,n}^{-}}^{\varepsilon} \right\}^{1/\varepsilon} \quad (15)$$

Ideal and anti-ideal values are depicted among all values of forest areas with SV > 0 in a specific scenario. R.forcircular works on a raster basis, and the elementary unit of each map is represented by a pixel. Therefore, ideal and anti-ideal values are the best and the worst scores among all pixels. Specifically, they are denoted as: ${v^+}_{i,n}$: maximum value for $i1$, $i3$, $i4$, $i5$, $i6$ and $i7$; minimum value for $i2$. Conversely, for ${v^-}_{i,n}$.

The metric ε expresses the level of compensation among indicators (Carver 1991). The model applies a default value equal to 1 for the metric ε, meaning a total compensatory approach.

The DSS also reports the average values in the study area for indicators $i1$, $i2$, $i5$, $i6$ and $i7$ and DIP as well as the total value (sum) for $i3$ and $i4$.

Case study and scenario analysis

The study area was the Municipality Union of Valdarno and Valdisieve (province of Florence, Tuscany region, Italy) (Fig. 1).

The territory is a mountainous area located in the central Apennines. The surface of the Municipality Union is 49,500 ha with a forest index of 62%. Forests are mainly composed of broadleaved forests (84%), followed by conifer forests (10%) and mixed broadleaved-conifer forests (6%). The most represented forest types are mixed broadleaved forests (50%), European beech (*Fagus sylvatica* L.)-dominated forests (15.5%) and oak (*Quercus* spp.)-dominated forests (14.5%). Regarding forest management, coppice systems are prevalent (83%) compared to high forests (17%). Public properties are managed in accordance with multifunctional principles, while private forests are mainly focused on productive functions due to the prevalence of small-sized coppices.

All geodata, coefficients and selections used to run the model are reported in "Appendices 1 and 2". The DSS was launched with a spatial resolution (squared pixel) of 10 m.

The hypothesised scenario takes into account a sensitivity analysis based on variation in the selling price for wood assortments (−20%, −10%, +10%, +20%) with respect to business as usual (BAU) as well as a higher level of mechanisation (HLM) of the production process. Specifically, this last scenario introduces high-power cable cranes (for steep terrain) and skidders (for non-steep terrain) in high forests; low-power cable cranes (for steep terrain) and skidders (for non-steep terrain) are hypothesised for coppices. Current applications of machinery (scenario BAU) correspond to ordinary mechanisation levels in both public and private properties assuming tractors with winches for both coppices (all slopes) and high forests in non-steep terrain as well as low-power cable crane in steep terrain in high forests. The variability of unitary costs for all machinery is reported in "Appendix 2".

Results

Table 4 indicates that maintaining the current level of mechanisation, the indicators generally improve as the selling price of wood assortments increases. The main wood product in the study area in terms of total amount was firewood followed by roundwood. The increase in wood assortments from scenario $p = -20\%$ to scenario $p = +20\%$ was particularly evident for timber poles (+1019%), followed by firewood (+810%), bioenergy (+463%) and roundwood (+46%). The financial performance expressed by the annual stumpage value (ϕSV) reached the best improvement among indices (+674%), with more moderate enhancement for

Fig. 1 Localisation of the study area in Italy

average annual stumpage value ($\overline{\phi SV}$: + 56%) and a decrease for average stumpage value (SV: − 28%). Strong improvement was revealed for the avoided CO_2 emissions (+ 483%). The majority of circular bioeconomy indicators also showed an improvement: the best performances were seen with *i*3 (+ 704%), *i*2 (+ 87%), *i*1 (+ 80%) and *i*4 (+ 70%). The other indices revealed balanced enhancement ranging from 4% with *i*7 to 15% with *i*6. The only indicator that showed a worsening with augmented prices was *i*5. In fact, the ratio between the potential economic value of the wood assortment and the real value earned in the local market increased from scenario $p = -20\%$ to scenario $p = -10\%$, but showed a decrease from $p = -10\%$ to $p = +20\%$. The SMCA output (DIP) indicates an improvement from the $p = -20\%$ to $p = +20\%$ scenario.

The application of HLM seemed to have conflicting results with respect to the other scenarios. The financial indicators were found to be the best with regard to the average stumpage value. Carbon dioxide-related indicators had an advantage in high-mechanisation scenarios for *i*2. Additionally, the production of roundwood showed improvement when compared with the scenario from $p = -20\%$ to $p = +10\%$. Other indicators revealed intermediate or worse performances compared to the alternative scenario. Therefore, the DIP was better only in the $p = -20\%$ hypothesis.

The application of higher prices for wood assortments led to an augmentation of the forest surface with a positive stumpage value (Fig. 2). Starting from scenario $p = -20\%$ showing 2544 ha, this value increased in scenario $p = -10\%$ (4013 ha), BAU (7109 ha), $p = +10\%$ (9283 ha) and $p = +20\%$ (12,599 ha). The trend previously explained for the HLM scenario was confirmed here by the forest surface with SV > 0, equal to 3260 ha.

Figure 3 highlights a spatial comparison between forest areas characterised by SV > 0 of the BAU and HLM scenarios. Specifically, the forest surface with financial efficiency of the production processes for both scenarios amounted to 4272 ha, and the BAU and HLM scenarios were—exclusively—convenient in 2837 and 423 ha, respectively. However, the superiority of the BAU scenario in terms of the annual stumpage value reached was highlighted at 6911 ha vs. 621 ha.

Despite the trend of the annual average stumpage value, an interesting result was represented by the geographical

Table 4 Results of wood assortment production, financial output and SMCA

Output	Symbol	Scenario $p = -20\%$	Scenario $p = -10\%$	Scenario $p = \text{BAU}$	Scenario $p = +10\%$	Scenario $p = +20\%$	Scenario high-mechanisation
General indexes							
Forest surface with positive stumpage value (ha)	F	2544	4013	7109	9283	12,599	3260
Roundwood (m^3/y)	$\alpha+\beta+\gamma+\delta$	5839	6380	7072	7651	8503	8203
Timber pole (m^3/y)	T	106	216	440	763	1183	137
Firewood (m^3/y)	w	3229	6926	13,033	20,671	29,372	3549
Bioenergy (MWh/y)	λ	3384	5616	9282	13,815	19,061	4214
Annual stumpage value (€/y)	ϕSV	59,943	105,647	183,321	300,406	464,236	102,341
Average stumpage value (€/ha)	SV	3710	3379	2965	2751	2671	5111
Average annual stumpage value (€/ha $\cdot y^{-1}$)	$\overline{\phi SV}$	23.56	26.32	28.68	32.36	36.85	31.39
Avoided CO_2 emission (t)	AE	906	1539	2571	3836	5285	1147
Indices of circular bioeconomy							
I1 (average) (€/m^3)	$i1$	5.64	6.65	7.57	8.79	10.18	7.46
I2 (average) (gCO_2/m^3)	$i2$	430	551	660	745	805	348
I3 (sum) (ha/y)	$i3$	70	142	259	404	567	83
I4 (sum) (m^3·years)	$i4$	198,269	222,375	256,352	290,237	336,245	277,250
I5 (average) (€/€)	$i5$	1.21	1.25	1.19	1.14	1.11	1.17
I6 (average) (%)	$i6$	12.2	13.0	13.6	13.9	14.1	11.9
I7 (average) (gCO_2/kWh)	$i7$	265	272	275	276	276	270
Distance from ideal point	DIP	3.77	3.62	3.55	3.49	3.41	3.76

assessment of DIP for both the HLM and BAU scenarios (Fig. 4): The map depicts how DIP was lower (a better result) by 2417 ha in the HLM scenario and 5114 ha in the BAU scenario.

The DSS r.forcircular facilitated the extrapolation of results from different geographical boundaries. Through zonal statistics, both the average annual stumpage value and DIP were computed for high forests and coppices to highlight differences between forest management options. The boxplots in Fig. 5 show higher average annual stumpage values for high forests than for coppices in every scenario (median values); the difference tended to increase from $p = -20\%$ (26.47 vs. 10.84 €/ha·y^{-1}) to BAU (43.80 vs. 17.58 €/ha·y^{-1}) and to decrease from BAU to $p = +20\%$ (56.38 in high forests vs. 26.69 €/ha·y^{-1} in coppices). The HLM scenario stresses a worsening with respect to BAU for both high forests (−23.5%) and coppices (−12.5%).

The best performance of coppices compared to high forests was evident for DIP (Fig. 6). For each forest management option, DIP improved, shifting from the $p = -20\%$ to $p = +20\%$ scenario (from 3.22 to 3.17 for coppices and from 4.17 to 4.05 for high forests). High-mechanisation solutions depicted intermediate levels of DIP (2nd and 3rd ranking for coppices and high forests, respectively, with median values equal to 3.14 and 4.12).

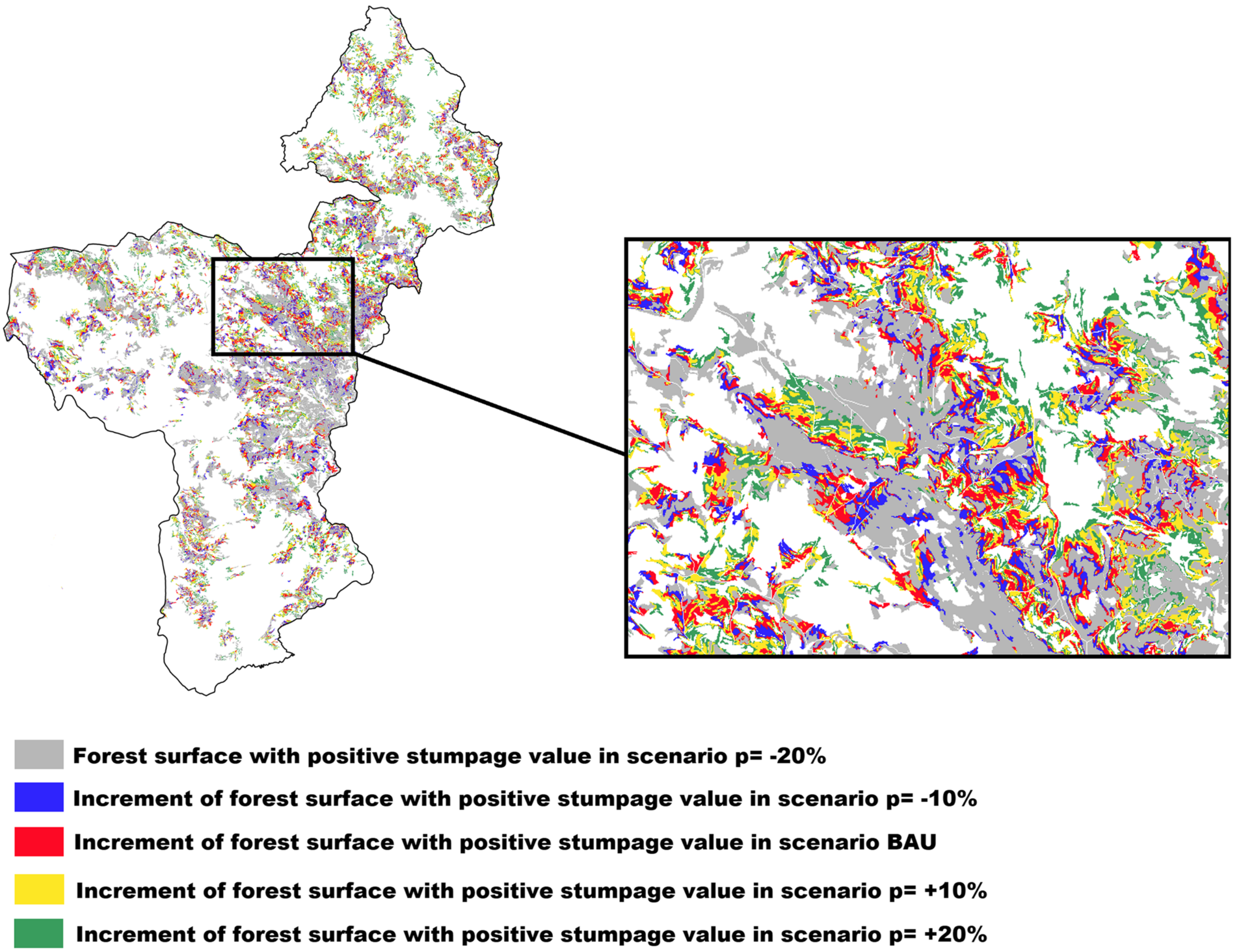

Fig. 2 Increase in forest surface with positive stumpage value from scenario $p = -20\%$ to $p = +20\%$ (highlighted in detail)

Discussion

The main wood product in the study area—in terms of total amount—was firewood, due to the prevalence of broadleaved coppices and a deep-rooted tradition in firewood production for domestic use. Firewood was followed by roundwood, mainly derived from reforestation with conifers that nearly all occurred in the 1970s (Cantiani and Chiavetta 2015). As expected, the increase in wood assortment prices led to an improvement in both the quantity of harvested material and the financial efficiency of the production process, except for the average stumpage value at harvesting (SV). Here, SV decreased because of the higher amount of forest surface with positive stumpage value; in other words, with low prices of assortments, only stands that reach high financial efficiency can be harvested. The compensation among indicators shows a more contained enhancement of the level of circular bioeconomy expressed by DIP. Another aspect confirms the variability between financial and circular bioeconomy performances: the average annual stumpage value was greater in the BAU scenario than in the HLM scenario by 6911 ha vs. 621 ha, respectively; however, DIP was better by 2417 ha in the HLM scenario and 5114 in the BAU scenario. This is a typical example of a trade-off among ecosystem services, in particular highlighting the potential contrast between provisioning and regulating cultural services or habitat maintenance (supporting services), as confirmed by various authors (Olschewski et al. 2010; Rose and Chapman 2003; Sacchelli 2018). The main advantage of DSS r.forcircular with respect to other trade-off evaluations is the representation of conflicts in spatial terms. This procedure is rarely included in GIS models in the international literature (Häyhä et al. 2015; Bottalico et al. 2016).

The dynamism of the roundwood market and the prevalence of low-quality forest species in coppices (e.g. *Quercus*

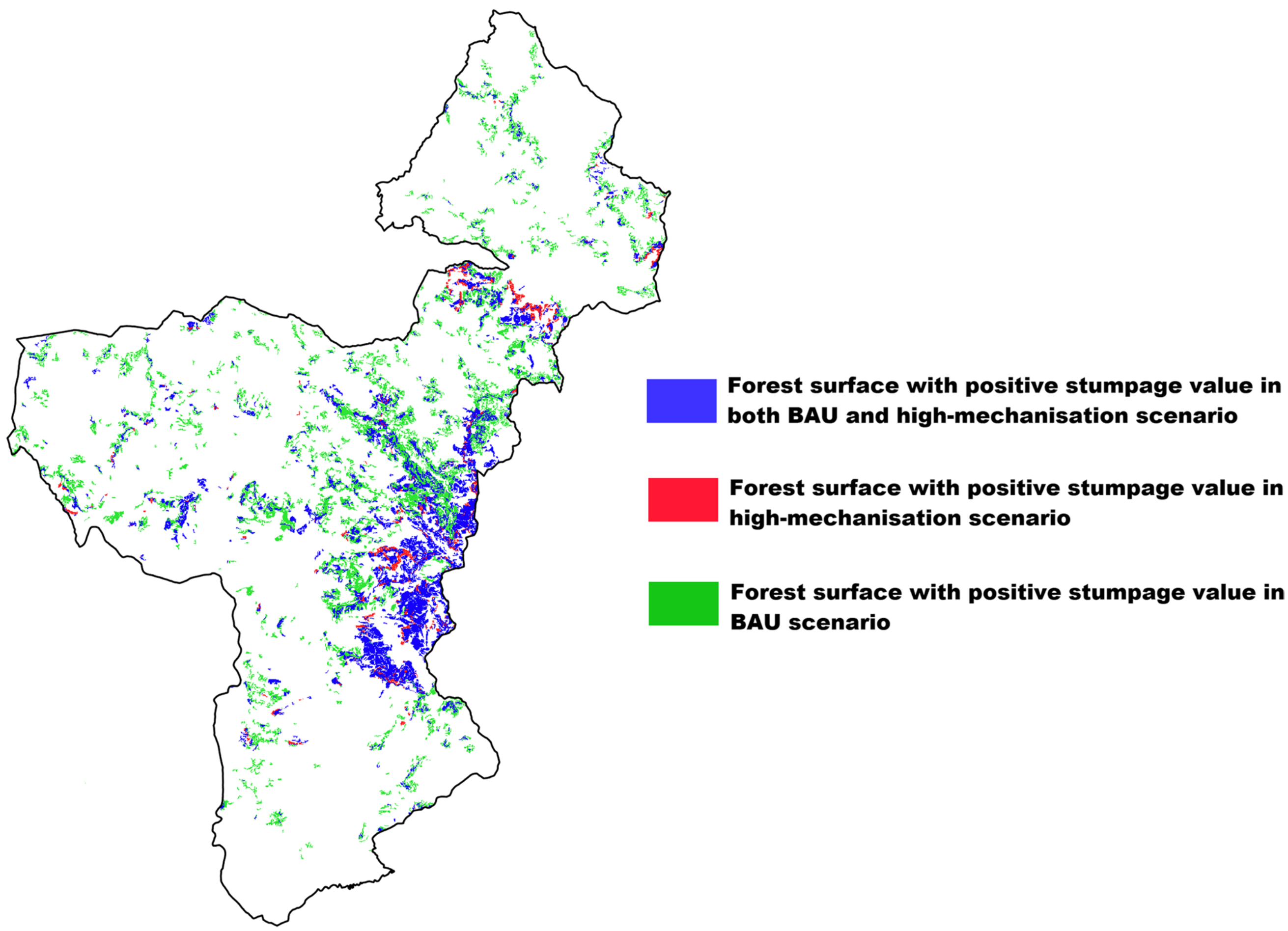

Fig. 3 Forest surface with positive stumpage value for the BAU and HLM scenarios

spp.) partially explains the differences in results between coppices and high forests. The average annual stumpage value was higher in high forests than in coppices; financial indices in coppices, however, seem to be more sensitive to the price of wood assortments. In fact, the availability of wood frequently follows a sigmoidal trend if computed by means of price-dependent sensitivity analysis (Sacchelli et al. 2013b). The affirmed market for products related to high forest with respect to coppices suggests how, in the present results, the elasticity for high forest could be lower. In other words, we are in the last part of the function, as confirmed by the low difference among stumpage values in high forests for scenarios $p = +10\%$ and $p = +20\%$. Therefore, small increments of improvement could be possible with augmentation of wood assortment prices.

The introduction of HLM in high forests and coppices does not make the production process more efficient than that of BAU from a financial viewpoint. The higher hourly cost of machinery is not compensated for by higher productivity, probably due to the low value of wood assortments and difficult work conditions (typical of mountainous areas).

HLM is more efficient than the BAU scenario in terms of circular bioeconomy (DIP value) for both high forest and coppices. Additional statistical analysis (spatial multiregression model, not reported in full) revealed how DIP for both the BAU and HLM scenarios is not correlated with slope and extraction distance. DIP quantification can be viewed as a typical multifaceted phenomenon in which various indicators are combined with each other and with geomorphological, logistic, vegetational, technical and economic variables. The application of the multicriteria approach facilitates the comparison of different scenarios. Accordingly, the DSS can be seen as a tool to investigate the forest circular bioeconomy in the framework of forest complexity (Corona 2016).

One limitation of this model is the need for a detailed land information system that is often not available at the local level in the national context. However, the flexibility of DSS r.forcircular allows the application of different input geodata and the consideration of default values for which information is not present (e.g. some dendrometric variables).

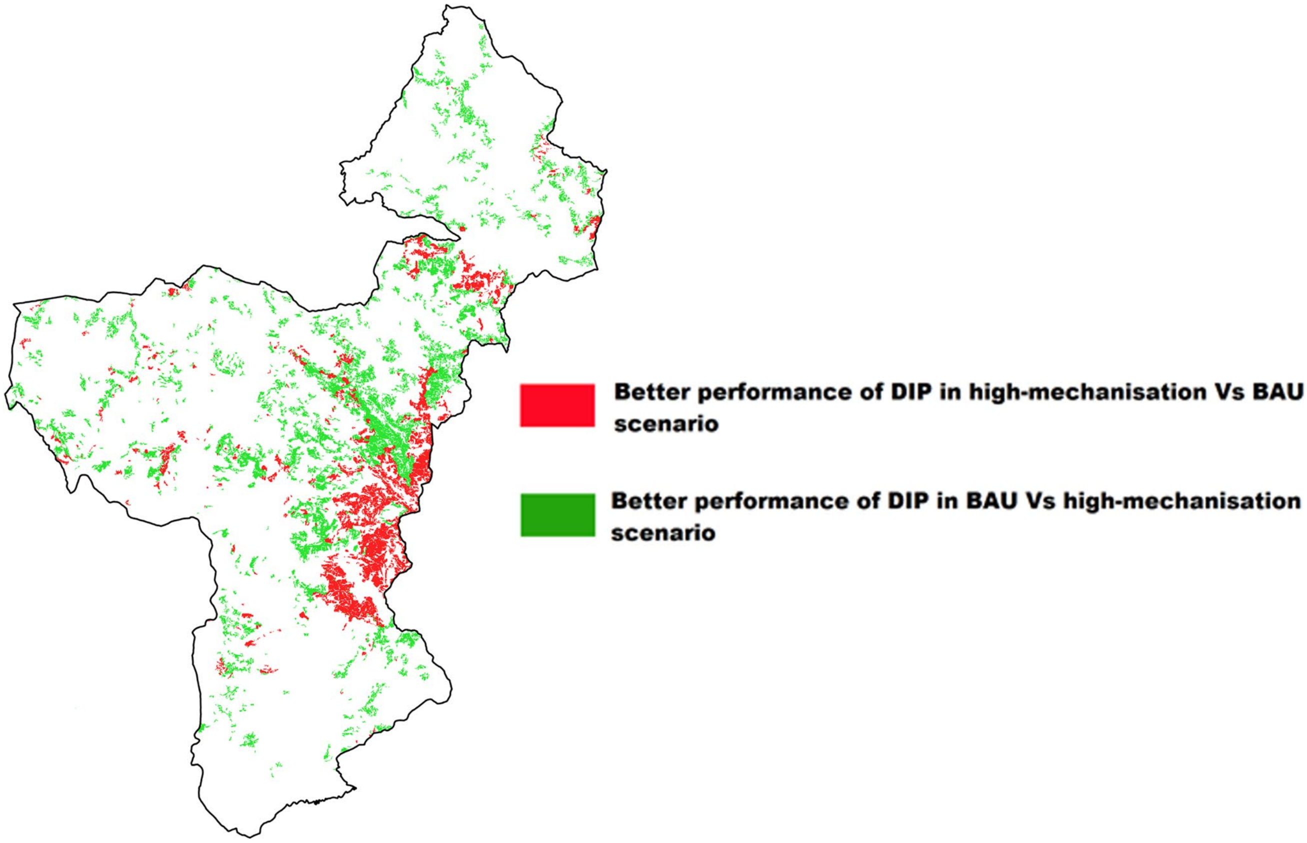

Fig. 4 Comparison of DIP in BAU and HLM scenarios

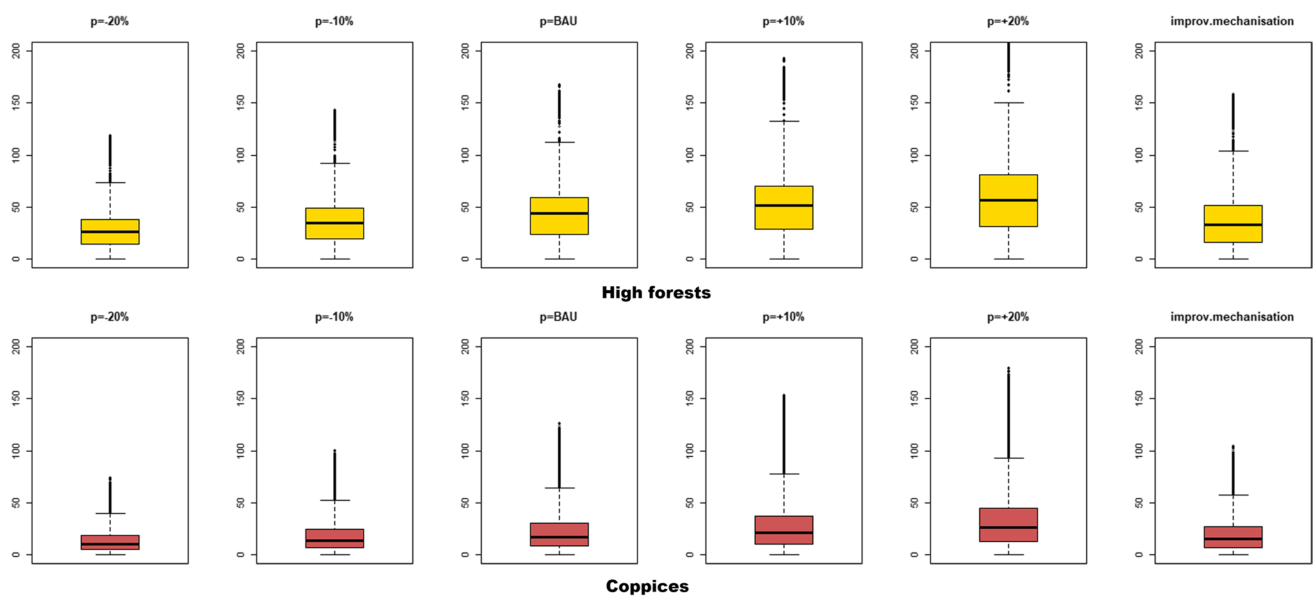

Fig. 5 Average annual stumpage value for high forests and coppices per scenario (€/ha·y^{-1})

The modular implementation of the DSS and the bash script-based structure allows for integrating the analysis with future additional indicators available in the international literature. Further improvements could provide an in-depth analysis of territorial variables, such as investigation of financial and circular bioeconomy performances among

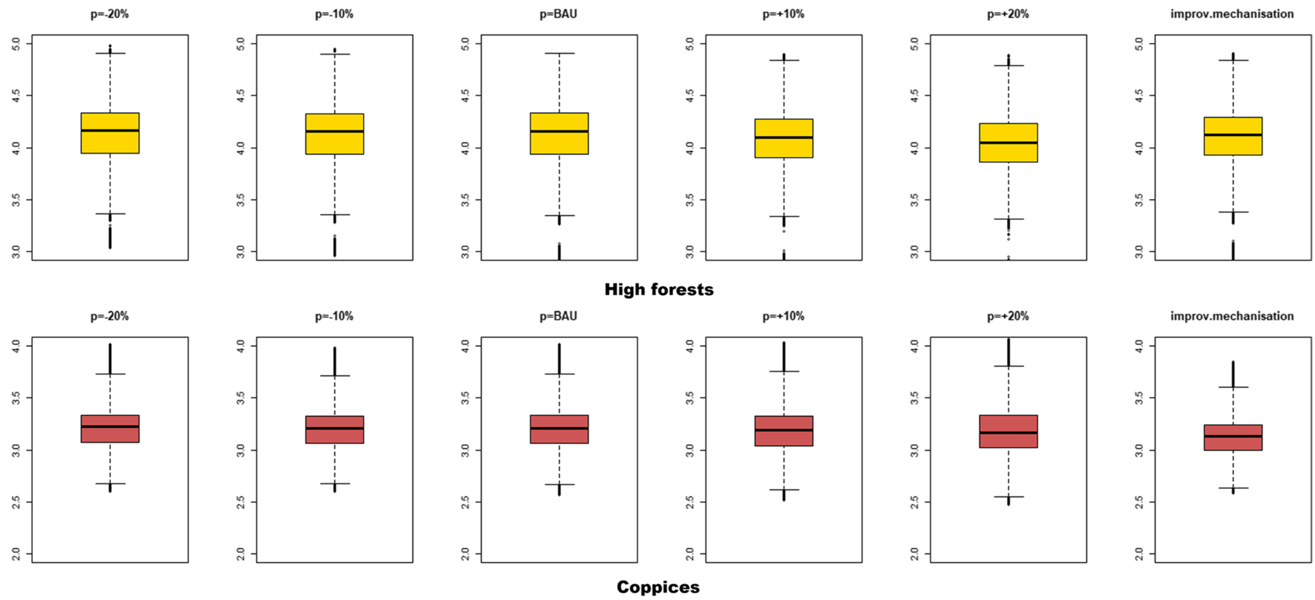

Fig. 6 DIP for high forests and coppices by scenario

forest categories. Different weights and/or metrics could be tested in the CP model to evaluate how compensation among criteria can influence the results.

Conclusion

The DSS r.forcircular was tested in the areas of the Municipality Union of Valdarno and Valdisieve, demonstrating the usefulness of accountability as applied in scenario and sensitivity analysis in the circular bioeconomy framework.

The model facilitates geographical analysis of the production process and user-friendly quantification of financial and bioeconomic indicators. The presence of GUI can promote innovation and technology transfer among different stakeholders. In addition, the DSS r.forcircular can support local decision-makers in achieving the objectives of the New EU Forest Strategy for 2030 with special regard to the implementation of the cascading principle as a main driver for changes in bioenergy policies, ensuring fair access to the biomass raw material market for the development of innovative, high value-added, bio-based solutions and a sustainable circular bioeconomy (European Commission 2021). The introduction of improvements suggested in the discussion section can serve to stimulate discussion of results and outputs from scenarios with policy-makers to deeply investigate strategies to improve the level of circular bioeconomy of the forest sector at the local level.

The next steps could be the application of the DSS to additional case studies in Italy, as well as to extend the indicators and SMCA framework, and to improve its user-friendliness for forest managers and decision-makers.

Appendix 1: Land Information System applied for the case study area

See Tables 5, 6, 7, 8, 9 and 10.

Table 5 Geodata, source and notes

Geodata	Source	Notes
Tracks	Land Information System of Tuscany region (http://www502.regione.toscana.it/geoscopio/cartoteca.html) and Openstreetmap Project (http://download.geofabrik.de/europe/italy.html)	For the Openstreetmap Project "Track" typology was selected for extraction (see the Track "Value" of Highway "Key" element in the classification available at: http://wiki.openstreetmap.org/wiki/Map_Features)
Boundaries	Municipalities from www.istat.it	Polygons of the following municipalities were selected: Londa, Pelago, Pontassieve, Reggello, Rufina e San Godenzo
Digital Terrain Model (DTM)	Land Information System of Tuscany region, http://www502.regione.toscana.it/geoscopio/cartoteca.html	–
Annual average increment	Grilli et al. (2020)	–
Management	Classification based on Tuscany Forest Inventory (http://www502.regione.toscana.it/geoscopio/cartoteca.html) and Sacchelli et al. (2013c)	–
Treatment	–	The value 1 was selected (final harvesting)
Roughness of terrain	Default value of r.forcircular	–
Mean tree diameter	Default value of r.forcircular	–
Mean tree volume	Default value of r.forcircular	–
Forest species or typologies	Land Information System of Tuscany region (http://www502.regione.toscana.it/geoscopio/cartoteca.html)	3rd level land use map updated with the project Tuscany Land Use Monitoring (MUST)
Soil productivity or fertility	Default value of r.forcircular	–
Rotation period	Regional forestry laws and regulations	See Table 6
Percentage of harvested trees during silvicultural intervention (treatment)	Analysis of local production process	See Table 7
Partitioning of increment in assortments	Analysis of local market; national norm tables from ISAFA (http://mpf.entecra.it/sites/default/files/pub_interne/)	See Tables 8 and 9. Sub-partitioning of roundwood: paper (2%), furniture (40%), building (50%), wood packaging (3%) or other (5%)
Price of assortment	Analysis of local market; Chambers of Commerce, Industry, Crafts and Agriculture; Wood Market analysis [Archivio Borsa Legno] of the Sherwood journal (http://www.rivistasherwood.it/extra/archivio-borsa-legno.html)	See Table 10
Mean low calorific value (LCV)	Hellrigl (2002)	–
Rivers	Life REWAT Land Information System (http://www.liferewat.eu/progetto-rewat/catalogo-dati.html)	–
Lakes	Land Information System of Tuscany region, http://www502.regione.toscana.it/geoscopio/cartoteca.html	–
Protected areas	Land Information System of Tuscany region, http://www502.regione.toscana.it/geoscopio/cartoteca.html	–

Table 6 Rotation period by forest category and management (years)

Forest category	High forest	Coppices
Picea abies Karst. and *Abies alba* Mill	70	–
Other broadleaves	–	8
Ostrya spp. and *Carpinus* spp.	–	18
Castanea sativa Mill	50	8
Quercus spp.	80	18
Cupressus sempervirens L	80	–
Fagus sylvatica L	90	24
Mixed forests of conifers	63	–
Mixed forests of broadleaves	60	20
Mixed forests of conifers and broadleaves	62	20
Pinus spp.	40	–
Robinia pseudoacacia L	8	8

Table 7 Percentage of harvested trees in final harvesting by forest category and management

Forest category	High forest	Coppices
Picea abies Karst. and *Abies alba* Mill	70%	–
Other broadleaves	–	100%
Ostrya spp. and *Carpinus* spp.	–	100%
Castanea sativa Mill	70%	90%
Quercus spp.	70%	80%
Cupressus sempervirens L	100%	–
Fagus sylvatica L	60%	80%
Mixed forests of conifers	70%	–
Mixed forests of broadleaves	70%	80%
Mixed forests of conifers and broadleaves	70%	70%
Pinus spp.	70%	–
Robinia pseudoacacia L	90%	90%

Table 8 Partitioning of assortments by forest category

Forest category	Roundwood (%)	Timber pole (%)	Firewood (%)	Woodchips (%)
Picea abies Karst. and *Abies alba* Mill	90	0	0	10
Other broadleaves	0	0	85	15
Ostrya spp. and *Carpinus* spp.	0	0	85	15
Castanea sativa Mill	0	15	70	15
Quercus spp.	0	0	85	15
Cupressus sempervirens L	90	0	0	10
Fagus sylvatica L	0	0	85	15
Mixed forests of conifers	90	0	0	10
Mixed forests of broadleaves	0	5	80	15
Mixed forests of conifers and broadleaves	27.5	5.0	55.0	12.5
Pinus spp.	90	0	0	10
Robinia pseudoacacia L	0	0	85	15

Table 9 Partitioning of assortments by forest category for quantification of indicator "*i5*"

Forest category	Roundwood (%)	Timber pole (%)	Firewood (%)	Wood-chips (%)
Picea abies Karst. and *Abies alba* Mill	90	0	0	10
Other broadleaves	0	0	90	10
Ostrya spp. and *Carpinus* spp.	0	0	90	10
Castanea sativa Mill	0	15	70	15
Quercus spp.	0	0	90	10
Cupressus sempervirens L	90	0	0	10
Fagus sylvatica L	0	0	90	10
Mixed forests of conifers	90	0	0	10
Mixed forests of broadleaves	0	5	80	15
Mixed forests of conifers and broadleaves	35	5	47	13
Pinus spp.	90	0	0	10
Robinia pseudoacacia L	0	0	90	10

Table 10 Price of assortments by forest category

Forest category	Roundwood (€/m^3)	Timber pole (€/m^3)	Firewood (€/m^3)	Bioenergy (€/MWh)
Picea abies Karst. and *Abies alba* Mill	111	0	0	18
Other broadleaves	0	0	44	18
Ostrya spp. and *Carpinus* spp.	0	0	75	18
Castanea sativa Mill	0	50	46	18
Quercus spp.	0	0	72	18
Cupressus sempervirens L	53	0	0	18
Fagus sylvatica L	0	0	63	18
Mixed forests of conifers	74	0	0	18
Mixed forests of broadleaves	0	50	56	18
Mixed forests of conifers and broadleaves	74	50	56	18
Pinus spp.	58	0	0	18
Robinia pseudoacacia L	0	0	43	18

Appendix 2: Additional data

See Tables 11 and 12.

Table 11 Other coefficients and base data applied for the case study area

Symbol	Unit of measure	Description	Value for the case study
$\overbrace{U_{s,g}}^{\text{set}}$	%	Upper limit of slope for ground-based extraction (set by user)	30
$\overbrace{U_{d,g}}^{\text{set}}$	m	Upper limit of distance for ground-based extraction (set by user)	800 in coppices; 900 in high forests
$\overbrace{U_{h,g}}^{\text{set}}$	From 0 to 3	Upper limit of roughness for ground-based extraction (set by user)	1
$\overbrace{U_{s,a}}^{\text{set}}$	%	Upper limit of slope for aerial-based extraction (set by user)	100
$\overbrace{L_{s,a}}^{\text{set}}$	%	Lower limit of slope for aerial-based extraction (set by user)	30.1
$\overbrace{U_{d,a}}^{\text{set}}$	m	Upper limit of distance for aerial-based extraction (set by user)	1000
u	€/h	Hourly unitary cost for the o phase	See Table 12
r	%	Interest rate	3
μ		Number of cycle for reuse of a specific assortments	Paper: 5, furniture: 1, building: 1, other assortments: 0
θ	%	Percentage of reuse of the product in every cycle	Paper: 80%, furniture: 10%, building: 90%
χ	y	Lifespan of products	Paper: 2, furniture: 20, building: 25, wood packaging: 3, other (from roundwood): 3, timber pole: 20, firewood: 1, bioenergy: 0.5
ρ	tCO_2/MWh	Conversion factor from produced bioenergy to avoided CO_2 emission due to use of fossil fuel in heating plants (Francescato and Antonini 2010)	320
τ	Adimensional	Weights for indicator of circular bioeconomy	$i1=0.15$, $i2=0.12$, $i3=0.12$, $i4=0.13$, $i5=0.14$, $i6=0.17$, $i7=0.16$

Table 12 Hourly costs for o production phase

Process	Total hourly cost (€/h)
Felling and processing cost with chainsaw	13.17
Extraction cost with high-power cable crane	111.44
Extraction cost with medium-power cable crane	104.31
Extraction cost with skidder	64.36
Extraction cost with tractor	45.00
Chipping	160.87

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Availability of data and materials The datasets generated and/or analysed during the current study are available from the corresponding author on request.

Code availability The code developed during the current study will be available in GRASS GIS Add-on repository and directly from the corresponding author on request.

Declarations

Conflict of interest The authors have no financial or non-financial conflicts of interest to disclose.

Ethics approval This article has not been published previously; it is not under consideration for publication elsewhere; its publication is approved by all authors, and, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright holder.

References

Bais-Moleman AL, Sikkema R, Vis M, Reumerman P, Theurl MC, Erb K-H (2018) Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. J Clean Prod 172:3942–3954

Baldwin RF (2020) Forest products utilization within a circular bioeconomy. For Prod J 70:4–9

Bernetti I, Romano S (2007) Economia delle risorse forestali. Liguori editore, Naples

Biancolillo I, Paletto A, Bersier J, Keller M, Romagnoli M (2020) A literature review on forest bioeconomy with a bibliometric network analysis. J for Sci 66:265–279

Bottalico F, Pesola L, Vizzarri M, Antonello L, Barbati A, Chirici G, Corona P, Cullotta S, Garfì V, Giannico V, Lafortezza R, Lombardi F, Marchetti M, Nocentini S, Riccioli F, Travaglini D, Sallustio L (2016) Modeling the influence of alternative forest management scenarios on wood production and carbon storage: A case study in the Mediterranean region. Environ Res 144:72–87

Brandão AS, Gonçalves A, Santos JMRCA (2021) Circular bioeconomy strategies: from scientific research to commercially viable products. J Clean Prod 295:126407

Bruhn T, Naims H, Olfe-Krautlein B (2016) Separating the debate on CO2 utilisation from carbon capture and storage. Environ Sci Policy 60:38–43

Bugge MM, Hansen T, Klitkou A (2016) What is the bioeconomy? A review of the literature. Sustainability 8:1–22

Cantiani P, Chiavetta U (2015) Estimating the mechanical stability of Pinus nigra Arn. using an alternative approach across several plantations in central Italy. iForest Biogeosciences For 8:846–852

Carver SJ (1991) Integrating multi-criteria evaluation with geographical information systems. Int J Geogr Inf Sci 5:321–339

Chisika SN, Park J, Yeom C (2021) Paradox of deadwood circular bioeconomy in Kenya's public forests. Sustainability (switzerland) 13:7051

Corona P (2016) Consolidating new paradigms in large-scale monitoring and assessment of forest ecosystems. Environ Res 144:8–14

D'Amato D, Veijonaho S, Toppinen A (2020) Towards sustainability? Forest-based circular bioeconomy business models in Finnish SMEs. Forest Policy Econ 110:101848

European Commission (2018) A new bioeconomy strategy for a sustainable Europe. http://europa.eu/rapid/press-release_IP-18-6067_en.htm

European Commission (2021) New EU Forest Strategy for 2030. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels

Francescato V, Antonini E (2010) La combustione del legno. Fattori di emissione e quadro normativo. Veneto Agricoltura, Azienda Regionale per i Settori Agricolo, Forestale e Agroalimentare, Settore Bioenergie e Cambiamento Climatico. Legnaro (PD) Italy

Gonçalves M, Freire F, Garcia R (2021) Material flow analysis of forest biomass in Portugal to support a circular bioeconomy. Resour Conserv Recycl 169:105507

Gregg JS, Jürgens J, Happel MK et al (2020) Valorization of bio-residuals in the food and forestry sectors in support of a circular bioeconomy: a review. J Clean Prod 267:122093

Hansen E, Kangas J, Hujala T (2021) Synthesis towards future-fittest for mature forest sector multinationals. Can J for Res 51:871–878

Häyhä T, Franzese PP, Paletto A, Fath BD (2015) Assessing, valuing, and mapping ecosystem services in Alpine forests. Ecosyst Serv 14:12–23

Hetemäki L (ed) (2017) Future of the European Forest-Based Sector: Structural Changes Towards Bioeconomy. What Science Can Tell Us. European Forest Institute

Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232

Kumar A, Adamopoulos S, Jones D, Amiandamhen SO (2021) Forest biomass availability and utilization potential in Sweden: a review. Waste Biomass Valoriz 12:65–80

Linser S, Lier M (2020) The contribution of sustainable development goals and forest-related indicators to national bioeconomy progress monitoring. Sustainability (switzerland) 12:2898

Loiseau E, Saikku L, Antikainen R et al (2016) Green economy and related concepts: an overview. J Clean Prod 139:361–371

Mair C, Stern T (2017) Cascading utilization of wood: a matter of circular economy? Curr for Rep 3:281–295

Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, New York

Markard J, Raven R, Truffer B (2012) Sustainability transitions: an emerging field of research and its prospects. Res Policy 41:955–967

Millennium Ecosystem Assessment (2005) Ecosystem and human well-being: biodiversity synthesis. Island Press, Washington

Näyhä A (2021) Backcasting for desirable futures in Finnish forest-based firms. Foresight 23:50–72

Olschewski R, Klein A-M, Tscharntke T (2010) Economic trade-offs between carbon sequestration, timber production, and crop pollination in tropical forested landscapes. Ecol Complex 7:314–319

Paletto A, Becagli C, Bianchetto E et al (2021) Measuring and assessing forest-based circular bioeconomy to implement the National Sustainable Development Strategy in Italy. Aust J for Sci 4:251–278

Pieratti E, Paletto A, De Meo I et al (2019) Assessing the forest-wood chain at local level: A multi-criteria decision analysis (MCDA) based on the circular bioeconomy principles. Ann for Res 62:123–138

Romero C, Rehman T (2003) Compromise programming. In: Romero C, Rehman T (eds) Multiple criteria analysis for agricultural decisions, developments in agricultural economics series. Elsevier, Amsterdam, pp 63–78

Rose SK, Chapman D (2003) Timber harvest adjacency economies, hunting, species protection, and old growth value: seeking the dynamic optimum. Ecol Econ 44:325–344

Sacchelli S (2018) A decision support system for trade-off analysis and dynamic evaluation of forest ecosystem services. iForest Biogeosci for 11:171–180

Sacchelli S, Zambelli P, Zatelli P, Ciolli M (2013a) Biomasfor—an open-source holistic model for the assessment of sustainable forest bioenergy. iForest Biogeosci for 6:285–293

Sacchelli S, Fagarazzi C, Bernetti I (2013b) Economic evaluation of forest biomass production in central Italy: a scenario assessment based on spatial analysis tool. Biomass Bioenerg 53:1–10

Sanz-Hernández A (2021) Privately owned forests and woodlands in Spain: changing resilience strategies towards a forest-based bioeconomy. Land Use Policy 100:104922

Toppinen A, D'Amato D, Stern T (2020) Forest-based circular bioeconomy: matching sustainability challenges and novel business opportunities? Forest Policy Econ 110:102041

Weiss G, Hansen E, Ludvig A et al (2021) Innovation governance in the forest sector: reviewing concepts, trends and gaps. Forest Policy Econ 130:102506

Wenger J, Haas V, Stern T (2020) Why can we make anything from lignin except money? Towards a broader economic perspective in lignin research. Curr for Rep 6:294–308

References for the Appendixes

Grilli G, Fratini R, Marone E, Sacchelli S (2020) A spatial-based tool for the analysis of payments for forest ecosystem services related to hydrogeological protection. Forest Policy Econ 111:102039

Hellrigl B (2002) Numeri per la Dendroenergetica. https://www.yumpu.com/it/document/view/16159133/numeri-per-la-dendroenergetica-bernardo-hellrigl-

Sacchelli S, Fagarazzi C, Bernetti I (2013c) Economic evaluation of forest biomass production in central Italy: a scenario assessment based on spatial analysis tool. Biomass Bioenerg 53:1–10

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