



# Assessing logging residues availability for energy production by using forest management plans data and geographic information system (GIS)

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## Abstract

The aim of the work was to quantify the mass of logging residues (branches and tops;  $\text{t yr}^{-1}$  dry matter, DM) for energy generation starting from Forest Management Plans (FMP) data. The methodology was applied to public stands of an Italian district (area:  $3.60 \times 10^4$  ha; period: 2009–2018). Compared to the previous preliminary analysis, the potentially available residues were computed considering forest accessibility and road traversability, by combining FMPs data with a geographic information system (GIS). New issues that were assessed here were: (i) representation of stands consisting of multiple disconnected parts; (ii) calculation of producible residues by using different values of biomass expansion factors (Scenario 1, S1; Scenario 2, S2). The potentially available residues computed for the analyzed period were used to quantify the current sustainable supply. Then, the potentially generated heat (thermal energy, TE;  $\text{GJ yr}^{-1}$ ) and electricity (EE;  $\text{GJ yr}^{-1}$ ), and the potentially avoided  $\text{CO}_2$  emissions into the atmosphere (EM;  $\text{t yr}^{-1} \text{CO}_2$ ) related to the final combustion process were computed by assuming that the current supply of residues was used as woodchips in a local centralized heating plant currently operating. For both S1 and S2, the large difference between the potentially producible and the potentially available residues demonstrated that geodata are essential for reliable estimations. Moreover, as the required information for the GIS analysis can be easily found in databases made available by forestry authorities, the proposed approach can be applied also to other areas; this could be helpful to support local decision-makers in defining sustainable practices for residues recovery.

**Keywords** Energy generation · Geodata · Geographic information system · Forest management plan · Forest stand · Logging residues

## Introduction

In recent decades, the worldwide energy demand grew exponentially, ranging from 8588.9 million tonnes of oil equivalent ( $Mt_{oe}$ ) in 1995 to 13147.3  $Mt_{oe}$  in 2015 (Dong et al. 2020). Energy generation is one of the main aspects of each policy to promote a sustainable economic growth (Ahmad and Zhang 2020) and is currently one of the main challenges

of the human society (Zambelli et al. 2012). In recent years, the intensification of negative climate effects due to the increasing demand of energy from non-renewable sources promoted worldwide the use of renewable energy (Vasco and Costa 2009; Zhou et al. 2011; Ferranti 2014). Biomass is the most important renewable energy source in Europe (Faaij 2006; Viana et al. 2010; Ferranti 2014), and biomass-based energy represents a responsible way to address the environmental and energetic challenges and offset greenhouse gases (GHG) emissions from fossil fuels, reducing global warming (IMED 2013).

In 2016, renewable energy contributed to 17% of the gross final energy consumption of the EU; bioenergy represented 59% of all renewable sources, and more than 60% of the domestic biomass supplied for energy generation came from wood (Camia et al. 2021). While contributing to meet society's needs, producing energy from biomass can promote new employment for the local population and

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conservation of rural areas (Demirbas 2009). As shown by Camia et al. (2021), there was a general increase of 20% in the use of wood over the last two decades in EU, except for a reduction after the year 2008. In the same way, the use of wood for energy generation reached a peak in 2013 and then decreased.

Wood-based energy sources can be classified as (i) primary and (ii) secondary. Primary wood sources include stems and logging residues resulting from forest operations, i.e., tops, branches, stumps, non-commercial wood parts or small stems which fall on the forest floor during felling (EN ISO 16559 2014; IPCC 2006; Thiffault et al. 2014; Nilsson 2016); stemwood represents 55%, whereas tops, branches, stems of poor quality and other non-commercial wood parts contribute for the remaining 45% (Camia et al. 2021). Secondary wood sources include by-products of the forest industries (i.e., industries aimed at the production of long-lived wood products) and tertiary wood sources.

By-products from sawmilling are mainly used for wood pulp, panels manufacturing and energy (Jonsson and Rinaldi 2017), whereas side-streams from chemical pulping are used both in the chemical industry and for energy production (Hurmekoski et al. 2018). The demand of sawlogs is one of the main factors affecting the provision of primary wood sources, including wood for energy (Camia et al. 2018). Therefore, forest industries and wood-based energy production are interconnected and competing sectors (Jonsson and Rinaldi 2017; Camia et al. 2021); the supply of wood for energy strongly depends on the development of wood-based industries, meaning that an assessment of the wood-based bioenergy sector must also consider the by-products coming from forest industries (Camia et al. 2021).

Approximately 49% of the wood-based bioenergy production in EU currently comes from secondary sources, 37% from primary sources, whereas the remaining 14% is not reported in the official statistics, i.e., it is not classified as a primary or a secondary source (Camia et al. 2021). An important contribution to the wood-based bioenergy sector comes from coppice forests, which are particularly important in the Mediterranean countries, where they cover an area of  $1.7 \times 10^7$  ha, i.e., 89.5% of the total coppice area of EU (Unrau et al. 2018; Camia et al. 2021).

The availability of primary wood sources for bioenergy can also be affected by natural disturbances which, within a short period, might make a large amount of damaged and/or infected wood of poor quality unavailable to be used in the forest industries (Barrette et al. 2015; Gouge et al. 2021). Leaving fresh residues and damaged wood in the forest can increase the risk of fire, with the result that rejuvenation obstacles and damages from insects (e.g., *Ips typographus* L.) and diseases might occur (Spinelli et al. 2007; Alkan et al. 2014). This is particularly important in the Mediterranean countries, where the collection of small-diameter

stems, branches and needles is an efficient strategy to limit forest fires (Hetsch 2008). On the other hand, leaving a fraction of residues in the forest as deadwood is generally recommended for ecological-environmental functions, e.g., nutrient cycle, soil protection, water regulation, biodiversity, habitat conservation, and forest productivity (Pistorius et al. 2011; Sullivan et al. 2011; Sacchelli et al. 2013). Some conifers man-made forestry plantations are not thinned due to lack of market demand and low prices; in these cases, wood collection can provide an opportunity to reduce the density of the forest, making available space for tree growth and regeneration, and improving the habitat value for several species (EEA 2006). Sustainable extraction of residues allows for a higher stand productivity (EEA 2006; Camia et al. 2021), and wood should be used at a rate that would prevent the depletion of the ecosystems, by matching the needs of the local population with environmental protection issues (Sacchelli et al. 2013). Using wood for energy is an important action for both biodiversity conservation and climate change mitigation only if biomass is produced within the sustainable forest management (SFM) framework (Fiorese and Guariso 2010; Verkerk et al. 2011). The most suitable forest management should be adapted case by case to maintain a constant and balanced provision of goods and services over time according to the local socio-economic, political, and environmental conditions (Camia et al. 2021).

Geographic Information Systems (GIS) represent a powerful tool for foresters, technicians and operators for record keeping, analysis and decision-making processes, and provide essential information to record and update forest inventories, harvesting estimations, as well as for landscape planning and management (Upadhyay 2009; Sonti 2015). The use of GIS and forest models can help forestry authorities and local decision-makers to better plan the supply of logging residues with the aim of developing sustainable energy plans. In mountainous areas, logging residues availability can be efficiently computed by using forest management plans (FMP) data and GIS.

For this work, studies concerning logging residues availability assessment through GIS were investigated through a systematic literature searching procedure (Schillaci et al. 2018). The research items were studied, and a robust pipeline was built to define: (i) spatial scale, (ii) environmental variables, and (iii) modeling approach. Literature was scrutinized to summarize the general bibliometric data (e.g., authors, title, journal, year of publication, abstract), to which site-specific data (e.g., characteristics of the studied area, used geodata, considered research paper) were added. The analyzed papers were subdivided into four main categories: (i) decision support systems, (ii) supply chain, (iii) power plants implementation, and (iv) assessment and prediction of biomass availability. Most of the time, two or more domains were considered in the same paper.

In the previous preliminary analysis, Nonini and Fiala (2021) presented the methodology implemented into the empirical forest stand-level model WOody biomass and Carbon ASsessment (WOCAS v2; Nonini and Fiala 2022) to calculate: (i) potentially producible residues ( $\text{t yr}^{-1}$  dry matter, DM), (ii) potentially available residues ( $\text{t yr}^{-1}$  DM), (iii) energy equivalent ( $\text{GJ yr}^{-1}$ ; tons of oil equivalent,  $\text{t}_{\text{oe}} \text{yr}^{-1}$ ), (iv) potentially generated thermal (heat) and electric energy ( $\text{GJ yr}^{-1}$ ) and (v) potentially avoided  $\text{CO}_2$  emissions into the atmosphere ( $\text{t yr}^{-1} \text{CO}_2$ ) related to the final combustion process. The methodology was then partially applied to the public forest stands of Valle Camonica district (Italy) for the period 1984–2016 (total forest area:  $3.67 \times 10^4$  ha).

The first aim of the present study was to develop the methodology presented by Nonini and Fiala (2021) to provide, for the Valle Camonica district, a more comprehensive assessment of the current sustainable supply of residues available for energy purposes at the stand and landscape level, i.e., the level of supply that can be maintained indefinitely without compromising the capacity of the ecosystem to provide goods and services for future generations (Hetsch 2008). For this first aim, the novelty was the combination of FMPs data with a digital elevation model (DEM) in a GIS software to consider also forest accessibility and road transitivity (traversability). The second aim of this study was to compare the results of two scenarios in which different values of biomass expansion factors were used (see Sect. 2). Finally, the third aim was to compute—by applying the methodology presented by Nonini and Fiala (2021)—the energy equivalent, the potentially generated heat and electricity, as well as the potentially avoided  $\text{CO}_2$  emissions into the atmosphere for both the scenarios, under the assumption that the current mass of residues at the landscape level was used as woodchips to feed an Organic Rankine Cycle (ORC) unit of a running local centralized heating plant, replacing fossil fuels. Valle Camonica was selected as a case study area as it is representative of several area of the Italian Alps and it is characterized by a rapid increment in the demand of woodchips for energy generation to support the ecological transition. In the valley, all the collected residues from public areas are comminuted into woodchips and used to feed a district heating plant, together with roundwood woodchips coming from both regional and non-regional forests. Nevertheless, no specific data on the mass of branches and tops are currently available; therefore, heuristic rules based on a set of empirical values and weights were used for the estimation.

## Materials and methods

### General modeling assumptions

#### Potentially producible residues

Calculations were performed by applying the methodology implemented into the second version of the stand-level model WOCAS v2 (Nonini and Fiala 2021, 2022). For a generic forest stand “ $j$ ” and for each analyzed year “ $n$ ,” the model quantifies the mass of potentially available logging residues (branches and tops only;  $RA_{n(j)}$ ;  $\text{t yr}^{-1}$  DM) starting from the potentially producible residues ( $RP_{n(j)}$ ;  $\text{t yr}^{-1}$  DM). The producible residues are computed as:

$$RP_{n(j)} = (MV_{Hn(j)} \cdot k_1 \cdot k_2) - MM_{Hn(j)} \quad (1)$$

where  $MV_{Hn(j)}$ : harvested merchantable stem volume ( $\text{m}^3 \text{yr}^{-1}$ ) for each stand “ $j$ ” and for each year “ $n$ ”;  $k_1$ : wood basic density, i.e., ratio between wood DM and wood fresh volume ( $\text{t m}^{-3}$  DM);  $k_2$ : biomass expansion factor, i.e., aboveground wood biomass DM on merchantable stem mass DM (dimensionless);  $MM_{Hn(j)}$ : harvested merchantable stem mass ( $\text{t yr}^{-1}$  DM) for each stand “ $j$ ” and for each year “ $n$ .”

According to a common classification adopted for Italian forests (Del Favero 2002), each stand is classified with three sub-criteria (SC): (i)  $SC_1$ : forest structure (e.g., simple coppice, compound coppice, coppice with standards, coppice under conversion, young high forest, mature high forest, irregular high forest), (ii)  $SC_2$ : forest function (e.g., production coppice, protection coppice, production conifers high forests, protection conifers high forests, production broadleaved high forests, protection broadleaved high forests) and (iii)  $SC_3$ : forest typology and variants (e.g., *Picea abies* L. of silicate substrates of mesic soils, *Picea abies* L. of silicate substrates of xeric soils, *Castanea sativa* Mill. of carbonate substrates of mesic soils, typical *Larix decidua* Mill., *Fagus sylvatica* L. of silicate substrates of mesic soils). Each SC is linked to a sub-code and the combination of the sub-codes originates a classification criteria code (CCC) to which specific calculation parameters are associated.

$RP_{n(j)}$  can be estimated by using, alternatively, (i) average values of  $k_2$  defined for each CCC (CCC-specific biomass expansion factors) or (ii) values estimated for each  $j$ -stand (stand-specific biomass expansion factors). In the first case, the same value of  $k_2$  is associated with all the stands classified through the same CCC, whereas in the second case, the values of  $k_2$  are specifically computed for each  $j$ -stand according to the merchantable stem mass at the starting year of the FMP. In both cases, the values of  $k_2$  are defined when the simulation starts and are assumed to be constant over time. The stand-specific values of  $k_2$  are computed according to Teobaldelli et al. (2009):

$$k_{2(j)} = k_3 + k_4/MM_{YRS(j)}^* \quad (2)$$

where  $MM_{YRS(j)}^*$  = merchantable stem mass per unit of area of the  $j$ -stand at the starting year of the FMP ( $t \text{ ha}^{-1} \text{ DM}$ );  $k_3, k_4$  = parameters of the non-linear regression function ( $k_3$ : dimensionless;  $k_4$ :  $t \text{ ha}^{-1} \text{ DM}$ ).

Further details on parameters selection are provided by Nonini and Fiala (2021, 2022) and in the Supplementary Information.

### Potentially available residues

$RA_{n(j)}$  is calculated as the product between  $RP_{n(j)}$  and a recovery rate ( $\eta_{(j)}$ , –) based on six technical parameters: (i) stand function, (ii) stand management system, (iii) energy market demand, (iv) harvesting method, (v) forest road transitivity (traversability) and (vi) stand accessibility. Each technical parameter is subdivided into different categories, and each of them is associated with a qualitative level (null; low; medium; high; maximum) classified by an empirical value (respectively: 0.00; 0.25; 0.50; 0.75; 1.00). Each parameter is then associated with a weight—ranging from 0 to 1—that defines the importance of the parameter itself on the implementation of the bioenergy supply chain. For each parameter, WOCAS v2 calculates a weighted value as the product between the empirical value and the weight previously defined; finally, for each stand,  $\eta_{(j)}$  is calculated as the sum of the weighted values of the six parameters.  $\eta_{(j)}$  is computed at the beginning of the simulation, it is assumed to be constant over time, and it is defined as the ratio between the residues which are potentially available for bioenergy and those which are potentially produced after the collection of the merchantable stem. In other words,  $\eta_{(j)}$  expresses the percentage of the producible residues which could be potentially available for energy generation. For further details, see Nonini and Fiala (2021).

### Energy equivalent, potentially generated energy and potentially avoided CO<sub>2</sub> emissions into the atmosphere

Assuming that the logging residues available at the landscape level are comminuted into woodchips to feed an ORC unit, WOCAS v2 calculates the energy equivalent ( $EQ_n$ ;  $\text{GJ yr}^{-1}$ ;  $t_{oe} \text{ yr}^{-1}$ ), the corresponding potentially generated heat and electricity ( $TE_n$  and  $EE_n$ , respectively;  $\text{GJ yr}^{-1}$ ), and the potentially avoided CO<sub>2</sub> emissions into the atmosphere related to the final combustion process ( $EM_n$ ;  $t \text{ yr}^{-1} \text{ CO}_2$ ), under the hypothesis that woodchips replace fossil fuels. The energy equivalent is computed by setting a range in the Lower Heating Value of the wood ( $\text{GJ t}^{-1} \text{ DM}$ ) and a conversion factor (from  $\text{GJ}$  to  $t_{oe}$ ) equal to  $41.86 \text{ GJ } t_{oe}^{-1}$ . The potentially generated heat and electricity are then quantified considering: (i) average thermal efficiency of the thermal

oil woodchip burners (–), (ii) average thermal efficiency of the ORC unit (–) and (iii) average electric efficiency of the ORC unit (–). The potentially avoided CO<sub>2</sub> emissions into the atmosphere associated to heat replacement are calculated according to: (i) Lower Heating Value of the substituted fossil fuel ( $\text{GJ m}^{-3}$ ), (ii) average thermal efficiency of the fossil fuel-based burners (–) and (iii) emission factor of the substituted fossil fuel (i.e., mass of emitted CO<sub>2</sub> per unit of fossil fuel volume;  $t \text{ m}^{-3} \text{ CO}_2$ ). Finally, the potentially avoided CO<sub>2</sub> emissions associated to electricity replacement are computed considering the emission factor of the electricity (i.e., mass of emitted CO<sub>2</sub> per unit of generated electricity;  $t \text{ GJ}^{-1} \text{ CO}_2$ ). For further details, see Nonini and Fiala (2021).

### Case study area and data collection

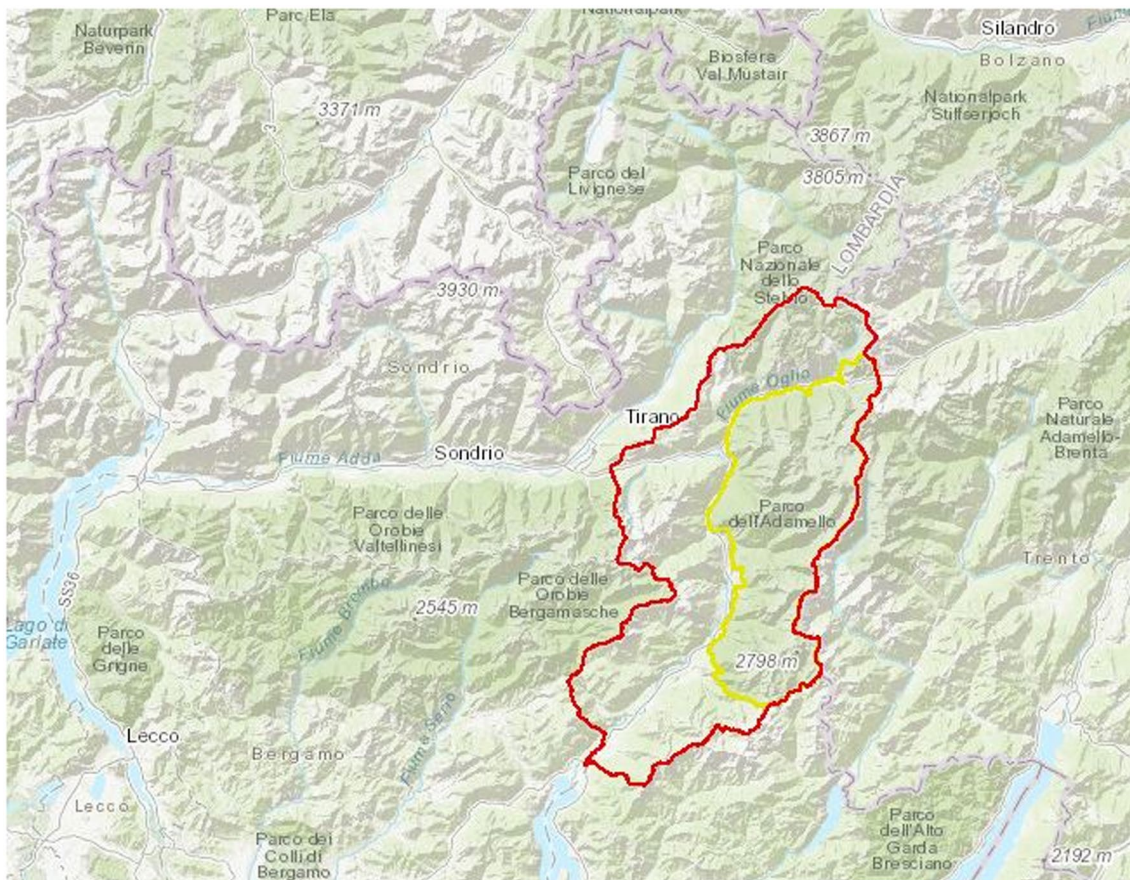
Valle Camonica is in the north-eastern part of the Lombardy Region, within the Rhaetian Alps (Fig. 1); it is characterized by a total area of  $A_T = 1.27 \times 10^5 \text{ ha}$  (12% of the mountainous area of the Lombardy Region) and a forest area of  $A_F = 6.58 \times 10^4 \text{ ha}$ . The forest cover index, i.e., ratio between the forest area and the total area, is 51.8%, almost double of that of the Lombardy Region (AAVV 2015). The eastern side of the valley is covered by the Adamello Regional Park, which encompasses more than 60% of the total area of the valley and includes 19 municipalities (Gerosa et al. 2013).

Forests are evenly distributed throughout the whole valley; private forests (not managed through FMPs) cover  $2.36 \times 10^4 \text{ ha}$  (36% of  $A_F$ ), whereas public forests (managed through FMPs) cover the remaining  $4.22 \times 10^4 \text{ ha}$  (64% of  $A_F$ ).

The main tree species of the district are: (i) *Picea abies* L. (30.0% of  $A_F$ ), (ii) *Larix decidua* Mill. (19.4%), (iii) *Alnus viridis* Chaix D.C., *Betula* L., *Corylus avellana* L., *Sorbus aucuparia* L., characterized by high physiognomic-structural disorders and occasional management (13.5%), (iv) *Alnus alnobetula* (Ehrh.) K. Koch (11.3%), (v) *Castanea sativa* Mill. (8.1%), (vi) *Fraxinus ornus* L. and *Ostrya carpinifolia* Scop. (5.1%), (vii) *Acer pseudoplatanus* L., *Tilia cordata* Mill. and *Fraxinus ornus* L. (3.9%), (viii) *Fagus sylvatica* L. (1.7%), (ix) *Larix decidua* Mill. in succession with *Picea abies* L. (1.6%) and (x) *Quercus petraea* (Matt.) Liebl., *Quercus pubescens* Willd., *Quercus cerris* L. (1.0%). The contribution of all the other tree species is lower than 1%.

For each  $j$ -stand, the required input data for the study were: (i) forest structure, (ii) forest function, (iii) forest typology and variants, (iv) forest area (ha), (v) harvested merchantable stem volume for each year in which cuts occurred ( $\text{m}^3 \text{ yr}^{-1}$ ) and (vi) merchantable stem volume of the stand per unit of area at the starting year of the FMP ( $\text{m}^3 \text{ ha}^{-1}$ ). These data were extracted from the “Cadastral FMPs database” (CPA v2), made available for free by the local forestry authority (i.e., the Mountain Community).





**Fig. 1** Valle Camonica district (red line) and Adamello Regional Park (yellow line) (Source: <https://www.sportellotelematico.cmvallcamonica.bs.it/gfmaplet/>)

Before the simulation, the values of the merchantable stem volume at the starting year of the FMP were converted into mass values through the parameter  $k_1$ .

The analysis covered the period 2009–2018. In the CPA v2, the merchantable stem volume of high forests expresses the volume over bark of the living stems with a diameter at breast height (i.e., 1.3 m above the forest floor) higher than 17.5 cm, from stump (30 cm above the forest floor) to a top diameter of 7 cm. Branches and foliage are excluded. The volume of conifers is estimated by using specific volume-diameter-height equations already applied for the Trentino-Alto-Adige Region, whereas the merchantable stem volume of broadleaved is always estimated by using, as a reference, the volume-diameter-height equation defined for the same Region for *Fagus Sylvatica* L. The merchantable stem volume of coppices is generally estimated by using standard values defined for each forest typology, according to the common classification adopted in Italy (Del Favero 2002). In the same way, the harvested volume of both conifers and broadleaved is referred to the merchantable stem and is computed by measuring in advance the diameters of the trees to be felled; in this way, there is an exact correspondence

between the authorized volume for cutting and the extracted one. The harvested volume of coppice is generally estimated at the landing site according to the volume of the trailer used for transport and can include also branches. Nevertheless, since the CPA v2 does not specify when this situation occurs for a given stand, also for coppice it was assumed that the volume is referred to the merchantable stem only.

According to a recent estimation of the Mountain Community carried out in the year 2015 (AAVV. 2015), the annual prescribed (planned through the FMPs) cutting volume of high forests is  $4.5 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$ , whereas the extracted volume is  $2.3 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$  (35% inside and 65% outside the Adamello Park, respectively). Therefore, 49%, approximately, of the annual prescribed cutting volume is left inside the forests as an additional potentially useful resource. The Mountain Community entrusts the management of the public forests to six forestry consortia and different logging companies. The merchantable stem is mainly delivered to the nineteen local sawmills, which annually process a volume of  $4.0 \times 10^4 \text{ m}^3$ , approximately; wood comes from both local and non-local forests (12.5%

and 87.5%, respectively), and is mainly used for packaging, pellet, beams, and planks (AAVV 2015).

A fraction of the harvested stems is currently comminuted into woodchips to feed the centralized heating plant of Ponte di Legno. Other feeding material of the plant is represented by woodchips produced from local logging residues and roundwood coming from non-local forests. The district heating plant (Table 1) was established in 2009 with a district heating and a thermal back-up unit and was recently equipped with an ORC unit for combined heat and electricity generation.

To calculate the potentially producible residues, the same values of  $k_1$  used by Nonini and Fiala (2021) were adopted, and two scenarios were investigated:

- Scenario 1 (S1; CCC-specific biomass expansion factors): the values of  $k_2$  reported in Federici et al. (2008), and already used by Nonini and Fiala (2021), were adopted; through S1, it was assumed that the stands are in equilibrium, excluding any dynamic effect related to volume or age;
- Scenario 2 (S2; stand-specific biomass expansion factors): the values of  $k_2$  were computed for each j-stand according to Eq. 2 by applying the values of  $k_3$  and  $k_4$  defined by Teobaldelli et al. (2009).

For further details, see Nonini and Fiala (2021) and the Supplementary Information.

To compute the potentially available residues, all the technical parameters defined in the previous preliminary study (Nonini and Fiala 2021) were considered. For the technical parameter n. 1 (stand function) and n. 2 (stand management system), the same qualitative levels and the corresponding empirical values adopted in the previous study were used. For the technical parameter n. 3 (energy market demand),

not having specific information, the qualitative level was set on “maximum” for stands with production function and on “low” for all the other stands.

For the parameter n. 4 (harvesting method), it was assumed that, for both conifers and coppices, wood collection occurred through the Full-Tree method (FT), which is currently the main method applied for these types of forests in the district. The qualitative level was therefore set on “maximum.” In the Alpine areas, FT is generally the most feasible harvesting method for conifers: the recovery of branches, tops, and all the other non-commercial components is integrated with roundwood production, allowing cost savings and simplified operations possible (Emer et al. 2011). Wood collection of broadleaved high forests is quite different and more technically complex compared to that of conifers since trees are more branchy and the branches—usually of larger diameter—are often obliquely inserted to the stem. Therefore, for all these stands, it was assumed that wood collection occurred through the Tree-Length (TL) method. The same assumption was adopted also for mixed high forest stands. The qualitative level was therefore set on “low.”

The technical parameter n. 5 (road traversability) and 6 (stand accessibility) were not made available by the CPA v2 and therefore were computed according to the topographic features, landscape morphology, and characteristics of the forest roads. To do this, a preliminary phase was performed to collect spatial coordinates (i.e., latitude, longitude), elevation and average slope of the stands. Firstly, all the stands listed in WOCAS v2 with their corresponding data were georeferenced by using the free and open-source software QGIS. The spatial coordinates of the stands, boundaries and area were obtained in the vector format from the public WebGIS Geoportal developed by the Mountain Community (<https://www.sportellotelema>

**Table 1** Technical characteristics of the Ponte di Legno plant. Heat and electricity are generated by using woodchips coming from both regional (local and non-local) and non-regional forests (40% and 60%, respectively) (Source Modified from Nonini and Fiala (2021))

Technical characteristics	
<i>District heating unit (starting year of activity: 2009)</i>	
Woodchips burners (heat transfer fluid: hot water)	2
Burners nominal thermal power; Average thermal efficiency	10.4 MW; 0.72
Year 2019: woodchips consumption; Operating time	$8.63 \times 10^3$ t ( $4.92 \times 10^3$ t DM); 7966 h
<i>Organic Rankine Cycle (ORC) unit (starting year of activity: 2017)</i>	
Woodchips burners (heat transfer fluid: thermal oil)	1
Burner nominal thermal power; Average thermal efficiency	4.04 MW; 0.75
ORC nominal thermal power; Average thermal efficiency	2.95 MW; 0.73
ORC nominal electric power; Average electric efficiency	0.73 MW; 0.18
Year 2019: woodchips consumption; Operating time	$1.34 \times 10^4$ t ( $7.65 \times 10^3$ t DM); 8121 h
<i>Thermal back-up unit (starting year of activity: 2009)</i>	
Diesel fuel burners (heat transfer fluid: hot water)	1
Burner nominal thermal power; Average thermal efficiency	8.0 MW; 0.85
Year 2019: woodchips consumption; Operating time	0 t (0 t DM); 0 h

[tico.cmvallecamonica.bs.it/page%3As\\_italia%3Ageoportale](http://tico.cmvallecamonica.bs.it/page%3As_italia%3Ageoportale)). In the “attribute table” of the shapefile, all the stands managed by the FMPs are listed and, to each of them, the spatial coordinates are associated. Like WOCAS v2, also in the “attribute table” each stand represents a record, organized in several fields containing specific input information. Each stand listed in WOCAS v2 and in the “attribute table” of the shapefile was marked with an alphanumeric unique code, by combining: (i) the alphanumeric code of the FMP through which the stand is managed and (ii) the number of the stand. For example, by combining “BS01” (FMP n. 1 of the district) and “01” (stand n. 1 of the FMP n. 1), the corresponding unique code was “BS01/01.”

Each stand listed in WOCAS v2 was then joined with its geographical data in the corresponding list of the “attribute table.” This operation was necessary to relate data of stands coming from different sources through a common field acting as a key.

For 118 stands, different types of errors were found in the “attribute table”, mainly related to: (i) stands with a different number compared to that reported in WOCAS v2, (ii) stands with no number, (iii) stands managed through to the same FMP and characterized by the same number. These errors were corrected by using the GIS geoprocessing tools and by collecting specific information from the local authority. At the same time, it was checked that the information related to characteristics of each stand (e.g.: forest structure, forest typology, forest function, merchantable stem volume at the starting year of the FMP, area) reported in the “attribute table” were the same as the ones reported in WOCAS v2. This preliminary phase showed that:

- For 55 stands out of 2019 extracted from the CPA v2 and listed in WOCAS v2, the join was not performed, since the corresponding shapefile was not made available;
- 1836 stands were made up of a single contiguous area, and therefore it was easy to define the centroids and the topographic features; 124 stands were made up of different non-contiguous area (from 2 to 14 sub-stands; on average 3 sub-stands per stands); in these cases, the mass of producible logging residues calculated by WOCAS v2 for the whole stand was subdivided among each sub-stand, proportionally to the area. Sub-stands smaller than 1000 m<sup>2</sup> ( $n = 49$ ) were excluded from the analysis.

Once the preliminary phase was completed, the forest road traversability and the stand accessibility were defined by combining the georeferenced stands and sub-stands with a DEM, made available by the Shuttle Radar Topography Mission (SRTM-DEM) at <https://portal.opentopography.org/raster?opentopoID=OTSRTM.082015.4326.1>. Data used in

this study referred to the year 2014 and were characterized by a spatial resolution of 1-arcsec (30 m) (Fig. 2).

Overall, 2157 polygons consisting of both single stands and sub-stands (Fig. 3) were analyzed (total forest area:  $3.60 \times 10^4$  ha).

Since, in WOCAS v2, the smallest management unit is the forest stand, to include in the analysis all the 2157 polygons, the methodology described in Nonini and Fiala (2021) to calculate the potentially available logging residues was directly implemented into GIS.

The average slope of the polygons was calculated in the centroid by using the software SAGA GIS (Schillaci et al. 2015), and it was assumed to be constant for the whole area. The centroid of each polygon was also assumed as a reference to calculate the distance from the nearest forest road. The map of the regional road system in the vector format and the forest roads data (year of update: 2019) were obtained from the Lombardy Region Geoportale for free at <http://www.geoportale.regione.lombardia.it/> (Fig. 4).

Table 2 and Table 3 show, for each traversability and accessibility class, the number of polygons (stands and sub-stands) and the average area (with the corresponding standard deviation).

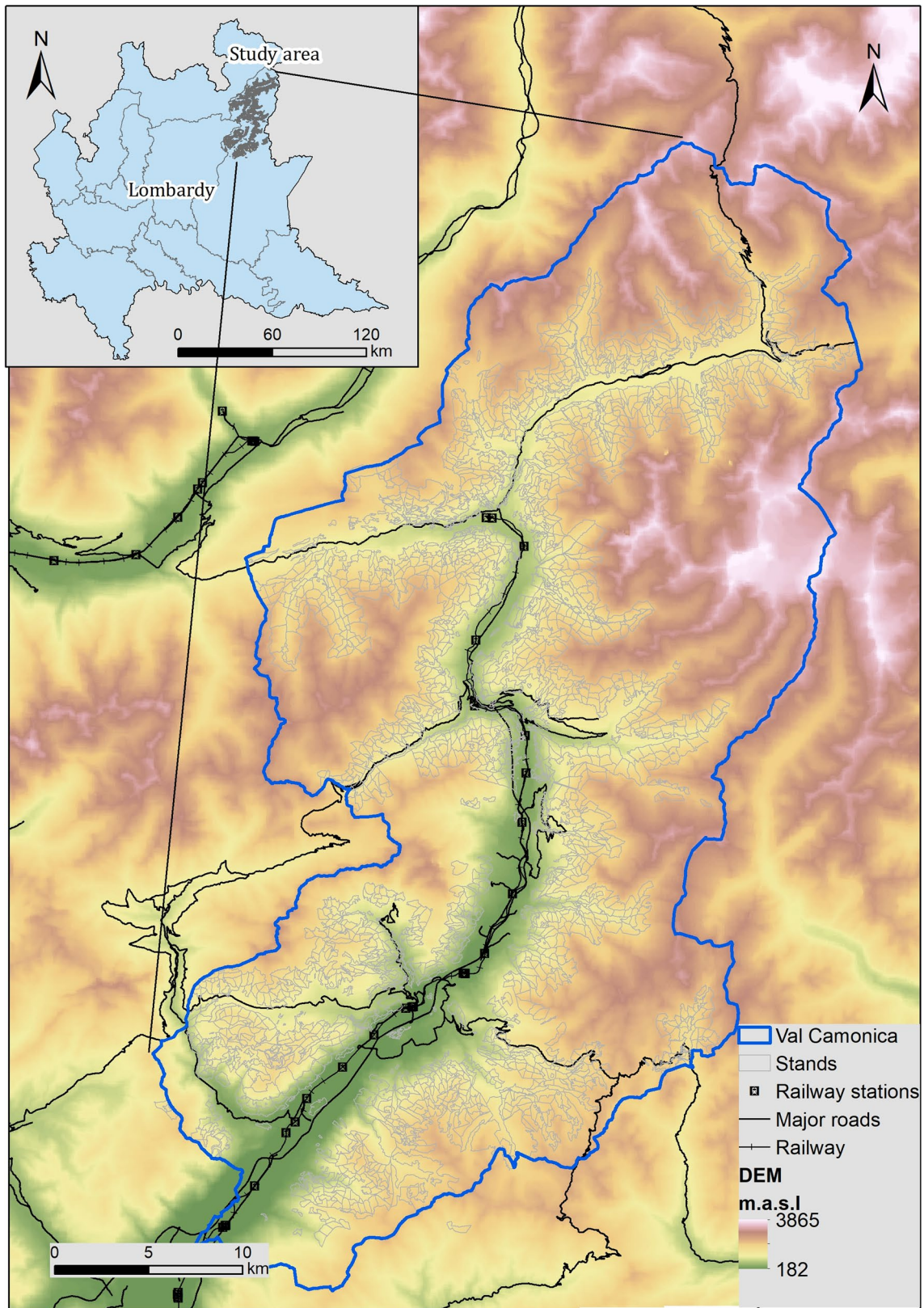
For forest road traversability and stand accessibility, the qualitative levels and the corresponding empirical values were assigned as described by Nonini and Fiala (2021). The same weight coefficient (i.e., 1/6) was assigned to each parameter, so that a balanced scenario was defined. Figure 5 summarizes the steps to calculate the potentially available residues by using FMPs data coming from the model WOCAS v2 (Nonini and Fiala 2021, 2022) and GIS.

Once the potentially available logging residues were calculated, the values were entered into the model WOCAS v2 to compute the energy equivalent, the potentially generated heat and electricity, and the potentially avoided CO<sub>2</sub> emissions into the atmosphere.

To compute the energy equivalent and the potentially generated energy, the minimum and the maximum Lower Heating Value of the wood was set equal to 17.5 GJ t<sup>-1</sup> DM and 20.5 GJ t<sup>-1</sup> DM, respectively (Nonini and Fiala 2021). The values of: (i) average thermal efficiency of the thermal oil woodchip burners, (ii) average thermal efficiency of the ORC unit and (iii) average electric efficiency of the ORC unit, were set equal to those reported in Table 1. The potentially avoided CO<sub>2</sub> emissions into the atmosphere were computed as follows (Nonini and Fiala 2021):

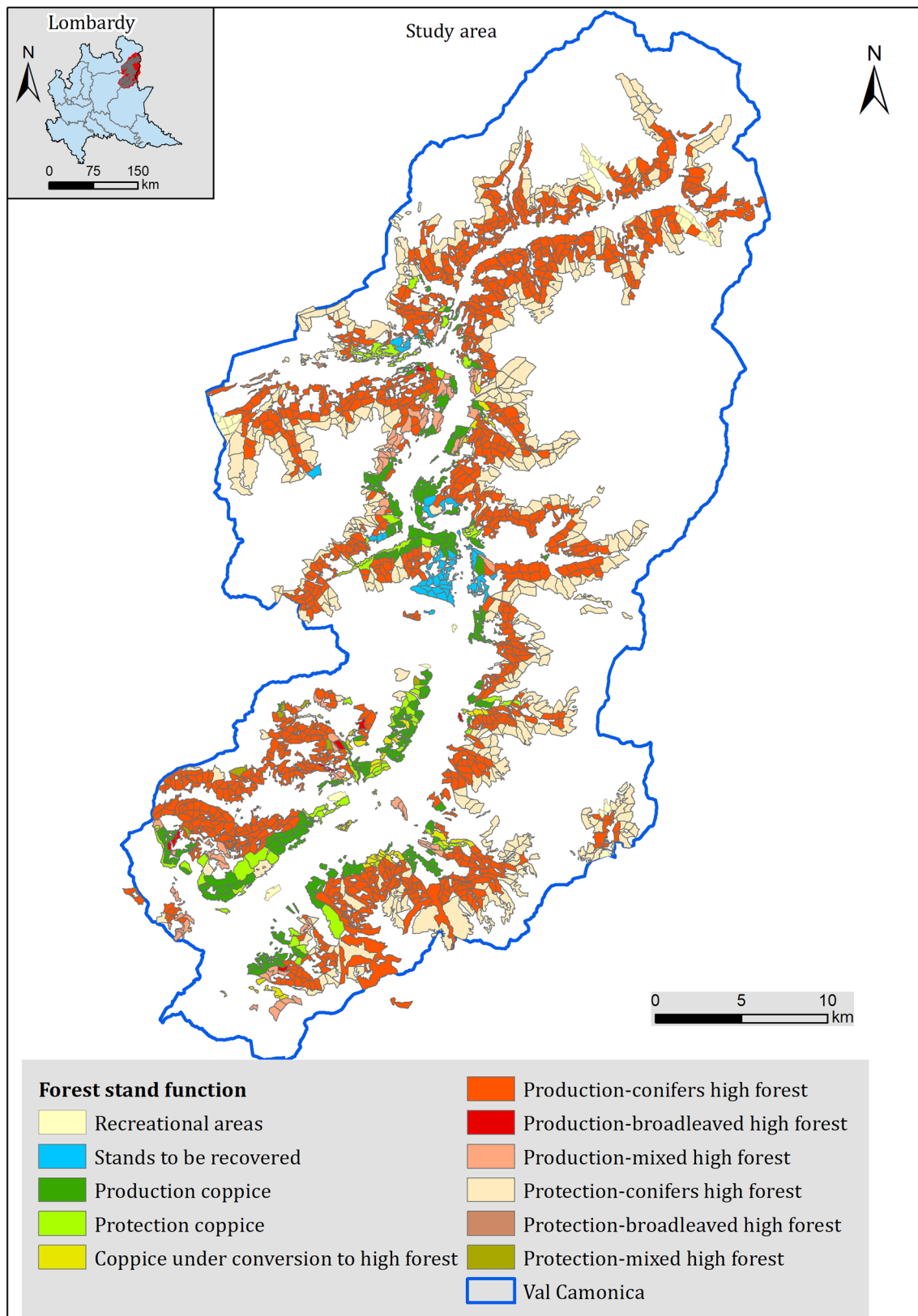
- the heat potentially generated by the ORC unit replaced the heat produced by conventional heating plants fed with natural gas, which currently represents the most used fossil fuel for heat generation in Valle Camonica;
- the electricity potentially generated by the ORC unit replaced the electricity distributed through the National



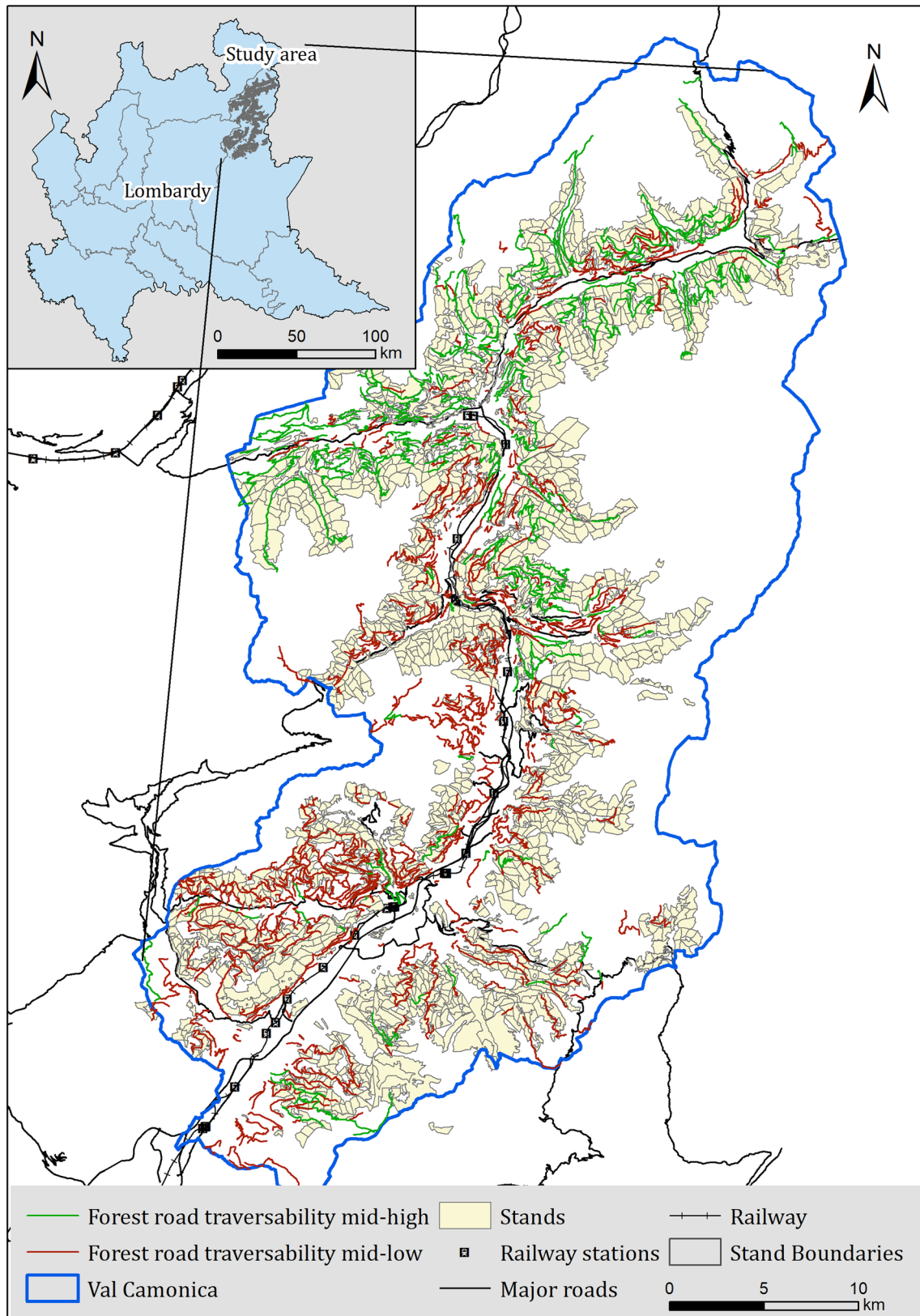


**Fig. 2** Digital Elevation Model (DEM) with a spatial resolution of 1-arcsec (30 m)

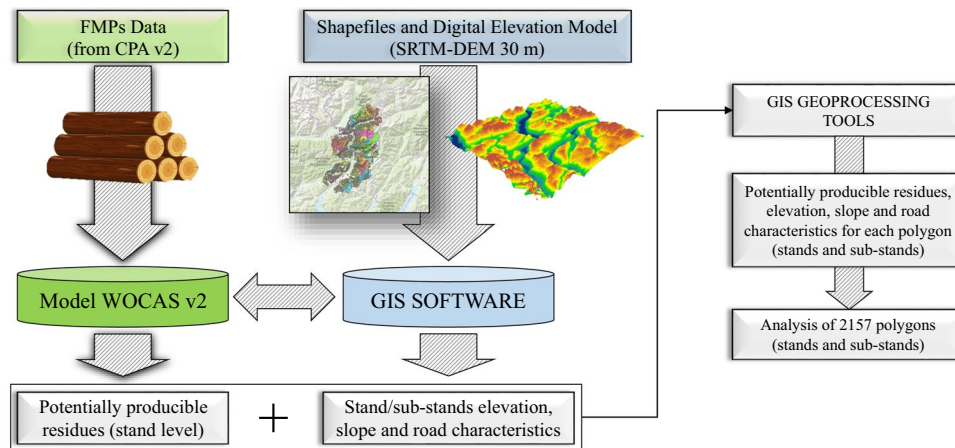




**Fig. 3** Distribution of the polygons (stands and sub-stands) according to the forest function



**Fig. 4** Distribution of the forest roads according to the traversability class



**Fig. 5** Schematization of the steps for the calculation of the potentially available residues (*RA*): Forest Management Plans (FMP) data registered in the Cadastral FMPs database (CPA v2) were extracted and used to calculate the potentially producible residues (*RP*) through the model WOCAS v2 (Nonini and Fiala 2021, 2022). Stands regis-

tered in WOCAS v2 and in the shapefile were then combined with a Digital Elevation Model (DEM) in a Geographic Information System (GIS) (Source of pictures: <https://tinitaly.pi.ingv.it/>; <https://www.freepick.com>; <https://www.sportellotelematico.cmvallcamonica.bs.it/>)

grid and produced by natural gas-based plants-mix for combined heat and electricity production.

The Lower Heating Value of the natural gas was assumed equal to  $3.53 \times 10^{-2}$  GJ  $m^{-3}$  (standard conditions) and a value of 0.85 was used for the average thermal efficiency of natural gas-based burners. The emission factors related to the natural gas was set equal to  $1.97$  t  $m^{-3}$  CO<sub>2</sub>, whereas for the electricity, a value of emission factor equal to  $9.81 \times 10^{-2}$  t GJ<sup>-1</sup> CO<sub>2</sub> was used. For further details, see Nonini and Fiala (2021).

## Results

### Potentially producible and potentially available logging residues

For the whole analyzed period (2009–2018), the total mass of the potentially producible residues ( $RP_{tot}$ ; t DM)—calculated as the sum of the potentially producible residues related to each stand and sub-stand—reached  $3.03 \times 10^4$  t DM and  $1.75 \times 10^4$  t DM for S1 and S2, respectively, whereas the total mass of the potentially available residues ( $RA_{tot}$ ; t DM) amounted to  $1.86 \times 10^4$  t DM and  $1.05 \times 10^4$  t DM for S1 and S2, respectively. The highest differences between S1 and S2 occurred in 2015 and were equal to 46.4% and 46.7% for *RP* and *RA*, respectively; the minimum differences took place in 2018 and were 31.1% and 34.6 for *RP* and *RA*, respectively. The inclusion of forest road traversability and stand accessibility in the calculation caused a reduction of the

potentially available residues of 16.4% and 15.6% for S1 and S2, respectively. Figure 6 shows, for both S1 and S2, the mass of potentially producible and potentially available residues.

From 2009 to 2015 the mass of *RP* and *RA* increased each year, except for 2010 and 2014; the highest mass of *RP* and *RA* occurred in 2015 (Fig. 6).

### Recovery rate of potentially producible logging residues

While the stand/sub-stand recovery rate does not change over time, the annual cumulative recovery rate—computed as the ratio between the annual potentially available residues and the annual potentially producible residues for all the stand and sub-stands—can change, since new stands/sub-stands with different characteristics can be included in the analysis due to the activation of new FMPs. At the stand/sub-stand level, the recovery rate ranged from 20.8 to 91.7%. Indeed, at the landscape level, the minimum and the maximum annual values were 59.1% (2010) and 64.1% (2017) for S1, and 57.6% (2011) and 63.6% (2017) for S2. For the whole analyzed period, the average recovery rate at the landscape level, calculated as the ratio between  $RA_{tot}$  and  $RP_{tot}$ , was  $\eta_{tot} = 61.5\%$  and  $60.2\%$  for S1 and S2, respectively (derived from Fig. 6). The current sustainable supply of residues was assumed to be constant and equal to the average value calculated for the whole period of analysis (2009–2018), i.e.,  $1.86 \times 10^3 \pm 7.01 \times 10^2$  t  $yr^{-1}$  DM and



**Table 2** Number of polygons, average area, and standard deviation for each traversability class (TC)

Traversability Class (TC) <sup>a</sup>	Polygons (stands and sub-stands)	
	Number (–)	Average area ± s.d. <sup>b</sup> (ha)
Medium–low (TC III + IV)	1376 (64%)	15.24 ± 10.38
Medium–high (TC I + II)	781 (36%)	19.26 ± 20.22

<sup>a</sup>The TCs are defined according to the Lombardy Region classification (2008) available at <https://www.regione.lombardia.it/wps/portal/istituzionale/HP/DettaglioRedazionale/servizi-e-informazioni/Imprese/Imprese-agricole/Boschi-e-foreste/normativa-boschi-e-foreste/viabilita-agro-silvo-pastorale/viabilita-agro-silvo-pastorale>; a description can also be found in Nonini and Fiala (2021)

<sup>b</sup>Standard deviation

**Table 3** Number of polygons, average area, and standard deviation for each accessibility class (AC)

Accessibility Class (AC) <sup>a</sup>	Polygons (stands and sub-stands)	
	Number (–)	Average area ± s.d. <sup>b</sup> (ha)
Insufficient (AC IV)	1069 (49.6%)	19.29 ± 18.17
Low (AC III)	184 (8.5%)	14.21 ± 8.50
Medium–high (AC II)	829 (38.4%)	14.36 ± 10.18
Maximum (AC I)	75 (3.5%)	11.65 ± 10.91

<sup>a</sup>The description of the ACs can be found in Hippoliti and Piegai (2000) and in Nonini and Fiala (2021)

<sup>b</sup>Standard deviation

$1.05 \times 10^3 \pm 3.76 \times 10^2 \text{ t yr}^{-1} \text{ DM}$  for S1 and S2, respectively. This assumption is valid only for a short period of time and only if forests maintain similar characteristics in terms of silvicultural treatments, total volume, and average productivity, and if natural disturbances and extreme events in general do not occur.

### Energy equivalent, potentially generated energy, and potentially avoided CO<sub>2</sub> emissions into the atmosphere

The energy equivalent ( $EQ$ ;  $\text{GJ yr}^{-1}$ ) at the landscape level related to the current sustainable mass of residues amounted to  $3.26 \times 10^4$ – $3.81 \times 10^4 \text{ GJ yr}^{-1}$  ( $7.78 \times 10^2$ – $9.11 \times 10^2 \text{ t}_{\text{oe}} \text{ yr}^{-1}$ ) for S1, and  $1.84 \times 10^4$ – $2.16 \times 10^4 \text{ GJ yr}^{-1}$  ( $4.40 \times 10^2$ – $5.15 \times 10^2 \text{ t}_{\text{oe}} \text{ yr}^{-1}$ ) for S2. Table 4 shows, for both S1 and S2, the energy equivalent, the potentially generated heat and electricity, the potentially avoided natural gas consumption and the potentially avoided CO<sub>2</sub> emissions into the atmosphere under the assumption that the estimated current mass of residues was used as woodchips to feed

the ORC unit of the local district heating plant of Ponte di Legno.

If the ORC unit was fed only with the local logging residues, the potentially generated heat and electricity would be equal to 0.71 and 0.18 MW, respectively, for S1, and 0.40 and 0.10 MW, respectively, for S2. The thermal and electric energy would be lower than the nominal thermal and electric one, and the average power load would amount to 0.24 and 0.14 for S1 and S2, respectively (Table 5).

## Discussion

### Potentially producible and potentially available logging residues

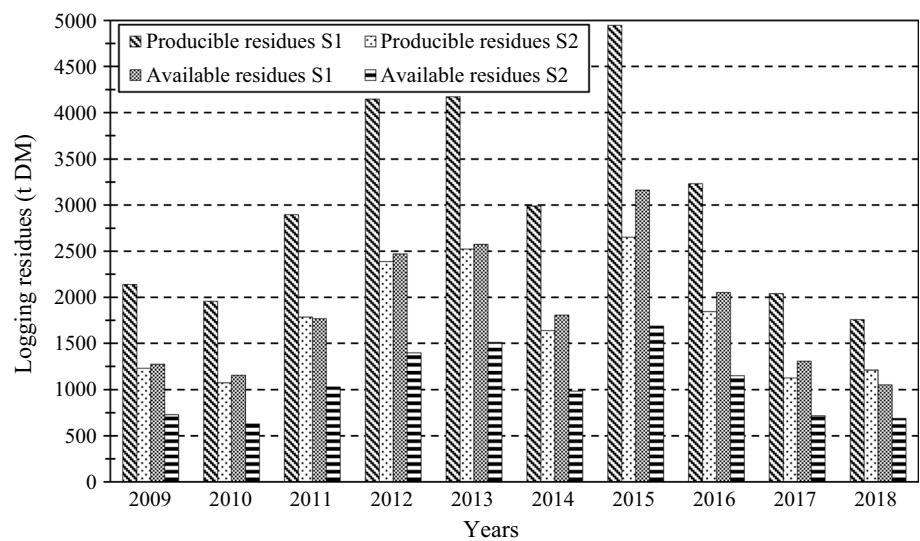
Several studies available in the literature are focused on the implementation of decision support systems to assess forest biomass availability at different scales (Fernandes and Costa 2010; Rørstad et al. 2010; Zambelli et al. 2012; Sacchelli et al. 2013; Statuto et al. 2013; Quinta-Nova et al. 2017), whereas others (Panichelli and Gnansounou 2008; Frombo et al. 2009; López Rodríguez et al. 2009; Viana et al. 2010; Geri et al. 2018; Abreu et al. 2020; Pergola et al. 2020; Van Holsbeeck and Srivastava 2020) are mainly focused on estimating the optimal location for installing a biomass power plant. These studies generally provide estimations at stand or regional scale, starting from the prescribed cutting volume, forest inventory, or literature data.

Indeed, through the modeling framework presented in this study, it was demonstrated that the potentially available logging residues for energy can be computed at the stand level starting from FMPs data and by applying biomass expansion factors. Moreover, logging residues are computed through a standardized methodology starting from the merchantable stem volume, which is always made available in the FMPs. This makes the modeling framework suitable for use also in other forest areas where the same input data are made available.

Another strength of this modeling framework is that it estimates the current supply of residues according to an historical analysis performed year by year on each stand, i.e., the residues that could have been collected under the assumption that certain conditions were met. This is essential for analyzing how the local resource was used over time and to evaluate its use for energy purposes when this can be done on a sustainable basis. Evaluating wood availability only according to the prescribed cutting volume might provide unreliable results, as the extracted volume may not be the same of the prescribed one.

Indeed, including in the modeling framework information currently missing such as the characteristics of the logistic chain, harvesting machines, cost (Spinelli and Magagnotti

**Fig. 6** Potentially producible (*RP*) and potentially available residues (*RA*) for S1 (CCC-specific biomass expansion factors) and S2 (stand-specific biomass expansion factors). For each year, the total value is the sum of the values associated to each polygon (stands and sub-stands)



2010; Verkerk et al. 2011; Zambelli et al. 2012), as well as the impact of biomass removal on forest multifunctionality and the trade-off among forest functions (Sacchelli et al. 2013) would certainly improve the reliability of the estimations. For this purpose, future research is needed.

Regarding the biomass expansion factor ( $k_2$ ), compared to the previous analysis,  $RP_{n(j)}$  was computed by applying both CCC-specific values (S1) as well as stand-specific values (S2). For the whole period of analysis, the total mass of potentially producible residues ( $RP_{tot}$ ; t DM) was equal to  $3.03 \times 10^4$  t DM for S1 and  $1.75 \times 10^4$  t DM for S2, whereas the total mass of potentially available residues ( $RA_{tot}$ ; t DM) reached  $1.86 \times 10^4$  t DM for S1 and  $1.05 \times 10^4$  t DM for S2.

For the case study area, using stand-specific values of  $k_2$  always caused a lower mass of residues compared to those obtained using CCC-specific values. Nevertheless, the method proposed by Teobaldelli et al. (2009) assumes that stands characterized by low volume (or mass) are also characterized by a low age and vice versa. Even if this generally occurs under real conditions, there might be situations where stands can have the same volume/mass but different ages, size (diameter and top height) and structure, according to environmental conditions, management practices and forest history. Therefore, this method for calculating biomass expansion factors should be further investigated. Moreover, the parameters of the regression function  $k_3$  and  $k_4$  were estimated from forests from all over the world; local values should always be preferred if available, and the method proposed by Teobaldelli et al (2009) should be applied only if the real characteristics of the stands are known and if specific values of  $k_3$  and  $k_4$  are made available at the local scale. This study clearly demonstrated that biomass expansion factors are a key variable in logging residues estimation, and this should be carefully considered when applying the

modeling framework in other forest areas of the world since using different values of  $k_2$  can lead to a considerable variation in the mass of the producible residues. This could be quite important for local authorities and decision-makers when evaluating the use of logging residues for energy generation at the local scale.

In the case study area, for both S1 and S2, the general increase in the mass of *RP* was directly related to the increase in the harvested merchantable stem mass and was mainly due to improvements in: (i) management of logging companies and (ii) forestry mechanization. The reduction in *RP* for 2010, 2014 and for the period 2016–2018 should be further investigated since, not having specific data related to the market trend, it was not possible to define with certainty whether these trends were due to aspect related to mechanization or a decline of wood market price. This is an important aspect, and it will be taken into consideration for future works on the case study area.

For both S1 and S2, the large difference between the potentially producible and the potentially available logging residues clearly highlights that including information on stand accessibility and forest road traversability is essential for reliable estimations; any eventual exclusion of these availability factors can be justified only for a preliminary analysis. This is another important aspect to consider when applying the modeling framework in other forest areas of the world. At the same time, besides FMPs data, the modeling framework is based on other data that can be easily collected, such as DEM and forest roads network. This makes it possible a straightforward application of the modeling framework in other forest areas than the one considered in this analysis.

The analysis presented here included the mass of the harvested wood used by the residents for personal use, which

**Table 4** Potentially generated energy, potentially avoided natural gas consumption and potentially avoided CO<sub>2</sub> emissions into the atmosphere for S1 (CCC-specific biomass expansion factors) and S2 (stand-specific biomass expansion factors) related to the use of local residues in the Organic Rankine Cycle (ORC) Unit

Type of energy	Potentially generated energy (GJ yr <sup>-1</sup> )	Potentially avoided natural gas consumption (m <sup>3</sup> yr <sup>-1</sup> ) (std. conditions)	Potentially avoided CO <sub>2</sub> emissions into atmosphere (t yr <sup>-1</sup> CO <sub>2</sub> )
<i>S1 (CCC-specific biomass expansion factors)</i>			
Heat	1.78 × 10 <sup>4</sup> –2.09 × 10 <sup>4</sup>	5.94 × 10 <sup>5</sup> –6.95 × 10 <sup>5</sup> <sup>a</sup>	1.17 × 10 <sup>3</sup> –1.37 × 10 <sup>3</sup> <sup>c</sup>
Electricity	4.40 × 10 <sup>3</sup> –5.16 × 10 <sup>3</sup>	2.13 × 10 <sup>5</sup> –2.49 × 10 <sup>5</sup> <sup>b</sup>	0.43 × 10 <sup>3</sup> –0.51 × 10 <sup>3</sup> <sup>d</sup>
Total	–	8.07 × 10 <sup>5</sup> –9.44 × 10 <sup>5</sup>	1.60 × 10 <sup>3</sup> –1.88 × 10 <sup>3</sup>
<i>S2 (Stand-specific biomass expansion factors)</i>			
Heat	1.01 × 10 <sup>4</sup> –1.18 × 10 <sup>4</sup>	3.36 × 10 <sup>5</sup> –3.93 × 10 <sup>5</sup> <sup>a</sup>	0.66 × 10 <sup>3</sup> –0.78 × 10 <sup>3</sup> <sup>c</sup>
Electricity	2.49 × 10 <sup>3</sup> –2.92 × 10 <sup>3</sup>	1.20 × 10 <sup>5</sup> –1.41 × 10 <sup>5</sup> <sup>b</sup>	0.24 × 10 <sup>3</sup> –0.29 × 10 <sup>3</sup> <sup>d</sup>
Total	–	4.56 × 10 <sup>5</sup> –5.34 × 10 <sup>5</sup>	0.90 × 10 <sup>3</sup> –1.07 × 10 <sup>3</sup>

<sup>a</sup>Average thermal efficiency of the household burners fed with natural gas: 0.85

<sup>b</sup>Average specific consumption of plants-mix for heat and electricity production fed with natural gas: 6.14 × 10<sup>3</sup> kJ kWh<sup>-1</sup> of gross electricity (Source TERNA 2018)

<sup>c</sup>Average emission factor for natural gas: 1.97 × 10<sup>-3</sup> t m<sup>-3</sup> CO<sub>2</sub> (Source Italian Ministry for the Environment 2018)

<sup>d</sup>Average emission factor of plants-mix for heat and electricity production fed with natural gas: 9.81 × 10<sup>-2</sup> t GJ<sup>-1</sup> CO<sub>2</sub> (gross electricity) (Source National Environmental Information System 2018)

**Table 5** Maximum thermal and electric power and average power load for S1 (CCC-specific biomass expansion factors) and S2 (stand-specific biomass expansion factors)

Type of power	S1 (CCC-specific biomass expansion factors)		S2 (Stand-specific biomass expansion factors)	
	Maximum value (MW)	Average Load <sup>a</sup> (–)	Maximum Value (MW)	Average Load <sup>a</sup> (–)
Thermal	0.71	0.24	0.40	0.14
Electric	0.18	0.24	0.10	0.14

<sup>a</sup>Computed as the ratio between the maximum value of the thermal and electric power (MW) and the ORC nominal thermal and electric power (2.95 MW and 0.73 MW, respectively, ref. Table 1)

should be excluded to avoid overestimations and improve the accuracy of the results. Nevertheless, information on such mass is not always made available by local FMPs. This should be carefully considered when applying the modeling framework in other forest areas of the world.

Even if the proposed methodology is based and the calculation of branches and tops only, an additional source of residues might origin from thinning operations of high forests (Zambelli et al. 2012). In these cases, however, problems of financial sustainability may occur, and the inclusion of this type of wood as an energy source should be evaluated case by case according to the profitability of the harvesting operations (Laitila et al. 2016; Lehtimäki and Nurmi 2011; Spinelli and Magagnotti 2010).

Another aspect to discuss strictly related to the case study area is that the potentially producible residues were computed until 2018 without taking into consideration the impacts of the Vaia storm (26–30th October, 2018) that, in

Valle Camonica, caused a loss of 8 × 10<sup>2</sup> ha of forest lands and 3 × 10<sup>5</sup> m<sup>3</sup> of merchantable volume, approximately. Therefore, it is reasonable to expect that the current mass of wood available for energy might be considerably higher than the one estimated through this analysis; because of this, further research is needed.

### Recovery rate of producible logging residues

The GIS analysis showed that many stands were made up of both contiguous and non-contiguous areas (sub-stands). Because of this, the methodology developed into the model WOCAS v2 was implemented into GIS. For each stand and sub-stand, the mass of RA<sub>n(j)</sub> was estimated by assuming that the technical parameters were all characterized by the same weight, i.e., they were all characterized by the same importance for the implementation of the energy supply chain. When applying the modeling framework in other areas of the world, it would be desirable to vary the weights of the parameters in order to evaluate different scenarios related to the increase/decrease of the potentially available residues. This would make the analysis more flexible, and it could be quite helpful for local decision-makers to define different management practices for residues supply.

The recovery rate is computed at the beginning of the simulation, and it is assumed to be constant over time. While it is reasonable to assume that stand function and management systems do not change year by year, the other parameters might change and the recovery rate might increase or decrease, causing a considerable variation of the potentially available residues. The computation of a recovery rate on annual basis undoubtedly makes the estimation more realistic and can better simulate the potential availability of



residues over time; this could be of practical help to optimize residues recovery. Nevertheless, problems of data availability might occur for some parameters. For example, the data on forest roads are generally updated among years, so that the data related to the years of update are overwritten on the older ones. For the case study area, forest road data updated for the year 2019 were used for the period 2009–2018; in other words, it was assumed that the number and the characteristics of the roads were constant for the whole period of analysis.

To define the accessibility, the slope of each stand/sub-stand was calculated in the centroid and assumed to be constant for the whole area. The centroid was also assumed as a reference to calculate the distance from nearest forest road. Even if it is done also in other studies (Frombo et al. 2009), it is an important assumption that need to be considered for further applications, especially for stands/sub-stands of large areas and in which the slope can vary considerably.

Since specific data on the harvested logging residues are not made available by the local FMPs, the validation of the results cannot be performed for the analyzed period. An evaluation of the accuracy of the results should be achieved through experimental tests to compute the real biomass that is collected at the stand level, in which different harvesting machines are used.

The results showed that at the stand/sub-stand level the recovery rate ranged from 20.8% to 91.7%, whereas, at the landscape level, it ranged from 59.1% (2010) to 64.1% (2017) for S1, and from 57.6% (2011) to 63.6% (2017) for S2. For the whole period of analysis, the average recovery rate at the landscape level amounted to 61.5% and 60.2% for S1 and S2, respectively. As a preliminary evaluation, these values can be directly compared to those reported by Thiffault et al. (2014), who analyzed 68 scientific studies and technical reports to investigate the recovery rates of logging residues for several stand types and region under different climatic, environmental, and operating conditions. The selected studies and reports were mainly based on the following harvesting methods: (i) Cut-to-Length (CTL), (ii) bundling and (iii) Full-Tree (FT). The authors found that the average recovery rate was equal to 52.2%, with a standard error of 18.1%. The distribution of the values resulted close to a normal one, with 70.6% of the values within one standard deviation of the average. The minimum value of the recovery rate was 4.0%, whereas the maximum amounted to 89.1%. The authors found that in stands of conifers—in which the uniformity of tree species, size and space facilitates the mechanized operations—the recovery rate was higher than in the broadleaved. For the CTL method, the authors reported an average recovery rate of 35.6%, approximately; for the FT, the average recovery rate amounted to 48.1% and 60.7% for operations performed during summer and autumn–winter or spring, respectively, since collecting

residues on a snowy area is generally easier compared to a heterogeneous one. None of the studies analyzed by Thiffault et al. (2014) defined the minimum mass of residues which should be left at the forest floor for ecological-environmental functions. In Italy, Spinelli et al. (2016) investigated *Picea abies* L. and hardwoods species in cable yarding and, when applying the FT method, they found that the recovery rate ranged from 10.0% to 70.0%, i.e., from 30.0% to 90.0% of biomass is left on site. For French forests, Cuchet et al. (2004) found that, when applying the CTL method, the recovery rate was 50.0%. Although these comparisons can be useful for a preliminary evaluation of the results of this study, it is worth pointing out that the values of the recovery rate provided by Cuchet et al. (2004), Thiffault et al. (2014) and Spinelli et al. (2016) resulted from empirical data of field trials, whereas the modeling framework presented here is based on the analysis of the potential availability, in which different technical parameters are taken into consideration at the same time. Each parameter represents an “availability factor,” i.e., a factor that can increase or decrease the potential available mass of residues; for this reason, for example, the modeling framework described here assumes that if in a stand with protection function a cut is performed, there is always a mass of potentially available residues because the extraction rate is always higher than 0. This should be considered when defining the sustainable residues supply.

Titus et al. (2021) developed a comprehensive review of existing guidelines for logging residues recovery from all over the world, focusing on guideline aims, environmental sustainability factors (e.g., soils and site productivity, biodiversity, water, and carbon), social factors (e.g., visual aesthetics, recreation), as well as preservation of cultural, historical, and archaeological sites. In Italy, there are currently no specific regulations or guidelines for residues recovery; for this purpose, participatory processes involving local forestry authorities and supply chain operators might be useful to define thresholds for residues extraction and limit the pressure on the environment (Hazlett et al. 2014).

### **Energy equivalent, potentially generated energy and potentially avoided CO<sub>2</sub> emissions into the atmosphere**

The energy equivalent at the landscape level was computed considering a range in the Lower Heating Value of wood. For further application, and to improve the accuracy of the results, the potential energy equivalent can also be estimated as the sum of the potential energy equivalent associated with each stand/sub-stand, considering specific Lower Heating Values according to the main species (Paganella et al. 2010).

The aim of this part of the study was to estimate the amount of heat and electricity associated with the use of

local woodchips and the corresponding potentially avoided CO<sub>2</sub> emissions into the atmosphere—related to the final combustion process only—if woodchips were used instead of fossil fuels to generate the same amount of energy. The analysis was not focused on the assessment of the energy and CO<sub>2</sub> balance of the bioenergy supply chain, nor the evaluation of the climate effects related to the use of wood. Therefore, as already defined in Nonini and Fiala (2021), the analysis of the potentially avoided CO<sub>2</sub> emissions into the atmosphere does not include the emissions which occur along the supply chain for wood collection, transport, and handling and storage, nor the biogenic emissions which occur during wood combustion. Further application of the modeling framework might include the comparison between the potentially generated energy and the current total energy consumption, as well as the comparison between the potentially avoided CO<sub>2</sub> emissions and the total CO<sub>2</sub> emissions which occur along the supply chain of the case study area.

## Conclusion

This paper presented a development of a methodology recently described in which the mass of the potentially available logging residues for energy purposes, and also the potentially generated heat and electricity and the potentially avoided CO<sub>2</sub> emissions into the atmosphere related to the final combustion process, are estimated for an Alpine area under the assumption that residues are used in a local district heating plant currently operating to replace non-renewable energy sources.

The novelty of this study was using GIS to collect data on forest road traversability and stand accessibility. The present study also demonstrated that residues availability can vary considerably according to the values of biomass expansion factors and harvesting sites. The modeling framework is based on input data which can be easily collected, such as FMPs, DEM, and forest road network; this simplicity enables a large application of the modeling framework also in other forest areas. Moreover, studies such as this one might help to feed into regional or global studies aimed at analyzing the role of forest biomass for bioenergy production in the context of ecological transition. To improve the reliability of the results for the case study area, collecting information on the harvested merchantable stem mass after the Vaia storm is essential; moreover, to solve the problem related to the subdivision of stands into sub-stands when performing the GIS analysis, it would be necessary: (i) to subdivide the stands into sub-stands also in the model WOCAS v2 and (ii) to integrate WOCAS v2 with a GIS software with the aim of developing an interactive GIS-based forest model. Moreover, in addition to constraints imposed by landscape conditions,

also harvesting machines should be considered for future works; using a machine rather than another is strongly related to the landscape conditions and terrain morphology, and this considerably affects the economic profitability of residues recovery.

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## Declarations

**Conflict of interest** The authors have no potential conflicts of interest to declare.

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