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Assessment of wood biomass and carbon stock and evaluation of machinery chains performances in Alpine forestry conditions: an innovative modelling approach

PhD Thesis: Luca Nonini

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Published scientific papers in peer-reviewed Journals

1. Fiala M., Marveggio D., Viganò R., Demartini E., **Nonini L.**, Gaviglio A. (2020). LCA and wild animals: results from wild deer culled in a northern Italy hunting district. Journal of Cleaner Production 244: 118667. https://doi.org/10.1016/j.jclepro.2019.118667

2. **Nonini L**., Schillaci C., Fiala M. (2020). Assessment of Forest Biomass and Carbon Stocks at Stand Level Using Site-Specific Primary Data to Support Forest Management. In: Coppola A., Di Renzo G., Altieri G., D'Antonio P. (eds). Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production. MID-TERM AIIA 2019. Lecture Notes in Civil Engineering 67: 501-508. Springer, Cham. https://doi.org/10.1007/978-3-030-39299-4_56

3. Fiala M., **Nonini L**. (2020). High Accuracy Site-Specific Secondary Data for Mechanical Field Operations to Support LCA Studies. In: Coppola A., Di Renzo G., Altieri G., D'Antonio P. (eds). Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production. MID-TERM AIIA 2019. Lecture Notes in Civil Engineering 67: 491-499. Springer, Cham. https://doi.org/10.1007/978-3-030-39299-4_55

4. **Nonini L**., Fiala M. (2019). Estimation of carbon storage of forest biomass for voluntary carbon markets: preliminary results. Journal of Forestry Research. https://doi.org/10.1007/s11676-019-01074-w

5. Fiala M., **Nonini L**. (2018). Biomass and Biofuels. In: Cifarelli L., Wagner F. (eds). Lecture Notes - Joint EPS-SIF International School on Energy - Course 4: Advances in Basic Energy Issues. EPJ Web of Conferences 189: 00006. https://doi.org/10.1051/epjconf/201818900006

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1. **Nonini L.**, Fiala M. Harvesting of wood for energy generation: a quantitative stand-level analysis in an Italian mountainous District. Scandinavian Journal of Forest Research (Under review).

Other published papers

1. **Nonini L.**, Quadri L., Fiala M. (2021). Uso della biomassa forestale residuale per fini energetici. Analisi quantitativa in un distretto montano. Rivista Sherwood – Foreste ed alberi oggi 252: 31-35.

Meetings, Conferences, Workshops and Symposia participation

1. **Nonini L.**, Fiala M. (2021). Harvesting of wood in an Italian district: a quantitative stand-level analysis. International Virtual Conference "Forestry: Bridge to the Future". May 5th – 7th 2021. Organized by: University of Forestry, Sofia, Bulgaria. Oral presentation.

2. **Nonini L.**, Cavicchioli D., Fiala M. (2021). Economic and environmental performances of forestry mechanization: an innovative approach. International Virtual Conference "Forestry: Bridge to the Future". May 5th – 7th 2021. Organized by: University of Forestry, Sofia, Bulgaria. Oral presentation.

3. **Nonini L.**, Schillaci C., Fiala M. (2020). Evaluation of forest logging residues availability for energy generation: a multicriteria Geographic Information System (GIS) approach. XI International Agriculture Symposium "AGROSYM 2020". Oct 8th – 11th 2020, Jahorina, Bosnia and Herzegovina. Virtual Conference. Oral presentation.

4. **Nonini L**., Schillaci C., Fiala M. (2019). Assessment of Forest Biomass and Carbon Stocks at Stand Level Using Site-Specific Primary Data to Support Forest Management. Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production. International MID-TERM AIIA Conference 2019. Sept 12th – 13th 2019, University of Basilicata, Matera (Italy). Oral presentation.

5. Fiala M., **Nonini L**. (2019). High Accuracy Site-Specific Secondary Data for Mechanical Field Operations to Support LCA Studies. Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production. International MID-TERM AIIA Conference 2019. Sept 12th – 13th 2019, University of Basilicata, Matera (Italy). Oral presentation.

6. Fiala M., Marveggio D., **Nonini L**. (2018). FACCE-SURPLUS ERA-NET Project: Modifying canopy architecture and photosynthesis to maximize barley biomass and yield for different end-uses (BarPLUS). III Meeting. WP4 – Task 4.3: In silico evaluation of potential barley ideotypes for grain and biomass production and evaluation of economic and environmental benefits – Environmental Assessment. Preliminary results. Mar 8th – 9th 2018, University of Lleida (Spain). Oral presentation

7. Fiala M., **Nonini L.**, Marveggio D. (2017). Sostenibilità ambientale delle operazioni meccaniche di campo. Conference: La meccanica agraria oggi. Un confronto aperto su concetti, idee e aspettative di una disciplina in continua evoluzione. Nov 23rd – 24th 2017, Free University of Bozen and NOI-Techpark, Bozen (Italy). Oral presentation.

Summary

The PhD Thesis focuses on **two topics**: (i) assessment of forest wood and carbon (C) stock and (ii) forestry mechanization applicable at the forest stand level for any given conditions among those found in the Italian Alpine and pre-Alpine mountainous areas. Both these topics aim to **improve the use of forestry resources** for climate change mitigation, starting from a **bottom-up approach** scaled on the information made available by **Forest Management Plans (FMP)**.

After an introduction on the topics given in chapter 1, the first topic **(assessment of forest wood and C stock)** is investigated in chapters 2, 3, 4 and 5, by taking the Valle Camonica District (Lombardy Region, Italy) as Case Study Area. The aim is to develop a **stand-level model** to estimate the mass of wood ($t \cdot yr^{-1}$ dry matter, DM) and C ($t \cdot yr^{-1}$ C) in aboveground wood biomass, belowground wood biomass and dead organic matter (i.e., deadwood and litter), quantifying, at the same time, the mass of **potentially available logging residues** (i.e., branches and tops; $t \cdot yr^{-1}$ DM) for energy generation and the corresponding potentially generated energy ($GJ \cdot yr^{-1}$), under the assumption that wood replaces non-renewable energy sources.

Chapter 2 presents the first version of the model, called "WOody biomass and Carbon ASsessment" (WOCAS v1), aimed at the quantification of the mass of wood and C in the forest pools in a predefined reference year, by using a methodology already applied at the regional and national level. The model was tested on a dataset of 2019 public forest stands extracted from **45 FMPs (area: 37000 ha)** covering the **period from 1984** (year in which the oldest FMP came into force) **to 2016** (most recent available data from the local FMPs). Preliminary results showed that, in 2016, the total C stock (given by the sum of C stock in aboveground wood biomass, belowground wood biomass, and dead organic matter) achieved 76.02 $t \cdot ha^{-1}$ C. The model also gives the possibility to analyze future scenarios based on the continuation of the current management practices rather than improved practices, to define a possible mitigation strategy for the activation of a local Voluntary Carbon Market.

WOCAS v1 was implemented into a second version (WOCAS v2), by introducing, first of all, an **improved methodology** to calculate the mass of wood ($t \cdot yr^{-1}$ DM) and C ($t \cdot yr^{-1}$ C) within the forest pools from the year in which the FMPs entry into force until a predefined reference year (chapter 3). The main innovative aspect of the improved methodology is that the gross annual increment of each stand is calculated through an **age-independent theoretical non-linear growth function** based on the merchantable stem mass, solving the limitation of WOCAS v1 in which the gross annual increment of the stand is assumed as constant, as reported by the FMPs. This improved methodology was applied to the same dataset used for WOCAS 1 (i.e., 2019 forest stands, 45 FMPs; forest area:

37000 ha; period: 1984-2016). The total weighted average wood yield, calculated as the sum of wood yield in all the above-mentioned forest pools, ranged from 53.36±53.13 $t \cdot ha^{-1} \cdot yr^{-1}$ DM (1984) to 156.38±79.76 $t \cdot ha^{-1} \cdot yr^{-1}$ DM (2016). The total weighted average C yield ranged from 26.63±26.80 $t \cdot ha^{-1} \cdot yr^{-1}$ C (1984) to 77.45±40.19 $t \cdot ha^{-1} \cdot yr^{-1}$ C (2016). The average C yield related to the whole analyzed period (1984-2016) was 66.04 $t \cdot ha^{-1}$ C. Of this, C yield in the aboveground wood biomass, belowground wood biomass and dead organic matter was equal to 72.0%, 15.8% and 12.2%, respectively.

Validation of the results at the stand level was performed by comparing the value of the gross annual increment provided by the FMPs with the one predicted by WOCAS v2. The model caused, in some cases, an overestimation and, in other cases, an underestimation. For example, for *Larix decidua* Mill. and for *Picea abies* L., the Pearson coefficient of correlation (r^2) between predicted and provided increments was $r^2 = 0.69$ and $r^2 = 0.46$, respectively. This was due to the fact that the methodology currently implemented into WOCAS v2 is based on average values of growth parameters valid for the whole Lombardy Region, and does not consider the productivity class of the stands since specific information was not always made available by the FMPs.

WOCAS v2 also includes an **innovative methodology** (chapter 4 and chapter 5) to quantify – as an additional climate change mitigation strategy – the mass of **potentially available residues** ($t \cdot yr^{-1}$ DM) for **energy generation**, the potentially generated heat and electricity ($GJ \cdot yr^{-1}$) and the potentially avoided CO_2 emissions into the atmosphere related to the final combustion process ($t \cdot yr^{-1}$ CO_2), under the assumption that wood substituted non-renewable energy sources. In chapter 4, since not all the required data were initially made available for the Case Study Area, the mass of residues was computed by considering only the stand's function and the stand's management system, covering the period from 1994 (year in which the first wood cut was performed) to 2016.

The calculation was then improved (chapter 5) by taking into account also the **stand's accessibility**, the **forest roads' transitability** and the energy market demand. Information on topographic features, landscape morphology and characteristics of the forest roads were collected by combining the FMPs data coming from WOCAS v2 and a **Digital Elevation Model (DEM)** in a **Geographic Information System** (GIS) software. The georeferenced stands were characterized by both single contiguous areas (single stands), as well as different non-contiguous areas (sub-stands). Overall, 2157 polygons – consisting of both single and sub-stands – were analyzed, covering the period from 2009 (most recent available data on forest roads' transitability) and 2016.

The mass of potentially available residues calculated for the analyzed period was used to estimate the **current sustainable supply** (i.e., $1.82 \cdot 10^3 \pm 6.61 \cdot 10^2$ $t \cdot yr^{-1}$ DM). Under the hypothesis that these residues were prepared into woodchips to feed the **Organic Rankine Cycle (ORC) unit** of the local centralized heating plant of Ponte di Legno, the potentially generated heat and electricity ($GJ \cdot yr^{-1}$) and the potentially avoided CO_2 emissions into the atmosphere ($t \cdot yr^{-1}$ CO_2) for the final combustion process were estimated by assuming that: (i) heat generated by the ORC unit replaced the one produced by natural gas-based heating plants; (ii) electricity generated by the ORC unit replaced the one generated by the Italian natural gas-based plants-mix for combined heat and electricity production and distributed through the National grid. Results showed that if only the current sustainable mass of residues was used to feed the ORC unit of the plant, the potentially generated heat and electricity would represent at most 28.7% of that generated by the unit in the year 2019. The thermal and electric power would be equal to 0.70 MW and 0.17 MW, with an **average power load** of the **ORC unit** of **23.6%.**

Experimental tests are needed to collect information on the harvesting method, used machines and technologies – which considerably affect the mass of available resides – as well as the currently harvested mass of residues for the validation of the results, that up to now is not possible since no measured data are available yet at the stand level.

The second topic **(forestry mechanization)** is investigated in chapter 6. The aim is to develop an **innovative approach** in order to: (i) select the most **suitable Forestry Machinery Chain (FMC)** to adopt at the stand level for wood collection (harvesting and transport) and (ii) compute the **economic costs** ($€ \cdot h^{-1}$; $€ \cdot t^{-1}$ DM; €) of the selected FMC.

To make the selection feasible, a **user-friendly stand-level model** called "FOREstry MAchinery chain selection" (FOREMA v1) was developed. FOREMA v1 supports the user in selecting the FMC according to seven technical parameters that characterize the stand. For each FMC, the model defines the **sequence of the operations** and the **types of machines** that can be used. The economic costs of the selected FMC are then quantified by taking into account the fixed and the variable costs. The approach was applied for a Case Study concerning the **collection of woodchips** from a coppice stand in the Italian Alps for **energy generation**. The analyzed FMC was made up of the following operations: (i) **felling**, (ii) **bunching & extraction**, (iii) **chipping** and (iv) **loading & transport**. For the whole FMC, the cost per unit of time was 669.3 $€ \cdot h^{-1}$; the cost per unit of product was 113.0 €·t DM, whereas the cost of production amounted to 6893.2 €. Results provided by FOREMA v1 still need to be validated; experimental tests are required to collect information on the operating conditions in which the machines are actually used and, consequently, on the corresponding economic costs. Obtained results on the costs of the operations were compared with that reported in literature and related to studies performed under similar forestry and operating conditions.

Chapter 1 – Introduction

1.1 General background

In Europe, forests cover approximately $2.27 \cdot 10^8$ ha (34.8% of the total area), which is about 5% of the world's forest area (Forest Europe, 2020). About 87% of the European forests is classified as semi-natural, 4% as natural, and 9% as plantations. Over hundreds of years, the climatic conditions, the environmental and hydrological factors, as well as the human practices led to the development of forests with different management systems, functions, and species.

The principles of **Sustainable Forest Management** (SFM)[1] recognize the **multifunctionality** of the forests and that they provide several **ecosystem services** that are crucial to the functioning of the biosphere. Such services can be split into the following categories (TEEB, 2010):

- provisioning services, which include products such as food (e.g., seeds, nuts and other fruit, spices, and fodder), wood and cellulose, aromatic plants, and pigments;
- regulating services, which include carbon sequestration, water regulation, protection from natural hazards (e.g., floods, avalanches, rock-fall, and erosion), water and air purification, disease, and pest regulation;
- cultural services, which include non-material benefits obtained from the ecosystem, such as recreation, sense of place, cultural heritage, education, aesthetic, spiritual and religious value.

Forests also provide services which are not included in the previous categories, despite being essential for the production of all the other services. These are the ecosystem functions themselves, such as photosynthesis, nutrients and hydrogeological cycle, soil formation, and habitat for species.

As the international community moved to address global warming and **climate change mitigation**, the role of forests received much more attention (EASAC, 2017). Climate change is widely recognized as a serious potential threat to the world's environment.

The problem is addressed through the **United Nations Framework Convention on Climate Change** (UNFCCC, 1992)[2] and the **EU Environmental Action Programs**[3]. The aim of the UNFCCC is to define a greenhouse gases (GHG) concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within

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1 The concept of SFM was introduced in 1993 by the Ministerial Conference for the Protection of Forests in Europe, and is defined as *"the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems"* (EASAC, 2017).

2 https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf

3 https://ec.europa.eu/environment/pdf/8EAP/2020/10/8EAP-draft.pdf

a time frame long enough to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner. An important step towards meeting the aim of the UNFCCC was taken in December 1997 through the **Kyoto Protocol**, which operationalized the UNFCCC by committing industrialized Countries and economies in transition to reduce GHGs emissions according to individual targets. In addition, the Kyoto Protocol widens the scope of the UNFCCC, reflected by the fact that the net emissions of CO_2 and other GHGs can also be reduced by removing these gases from the atmosphere. The Article 3.3 of the Protocol states that the emissions and removals of CO_2 and other GHGs resulting from the establishment of new forests (afforestation, reforestation) and from the conversion of forests into other forms of land use (deforestation) carried out after 1990 must be included in the National Inventory Report (NIR) that each Country listed in the Annex I of the Convention has to produce.

On the other hand, the Article 3.4 of the Protocol allows the accounting of emissions and removals of CO_2 and other GHGs related to the so-called additional activities – which include also **forest management** – as long as they occurred after 1990.

Moreover, the key role of forests in climate change mitigation was also recognized by the recent **Paris Agreement** (November 2016) – which defined the need to maintain the global temperature increase below 2 °C compared to the pre-industrial period – and the **EU regulation 2018/841 for the Land Use, Land Use Change and Forestry sector** (LULUCF) (Grassi et al., 2018; Nabuurs et al., 2018).

Forests absorb the atmospheric CO_2 and transform it into C for their growth through the process of photosynthesis. This C is firstly stored in the aboveground biomass, and then is transferred to other compartments, such as belowground biomass, dead organic matter (dead wood and litter) and soil (IPCC, 2006). The mass of the stored C (i.e., C stock) depends on the mass of wood and its dynamic, and therefore it can increase or decrease according to climate (e.g., temperature and precipitation), structure of forests (e.g., trees' density, species, and age), management practices and natural disturbances (e.g., fires, insect outbreaks, and windstorms). Therefore, by computing the trend of C stock over a given period of time, it is possible to assess to what extent forests compensate for or contribute to the GHGs emissions that occur in other sectors (EASAC, 2017; Forest Europe, 2020). In European forests, C stock is increasing, and this means that forests represent a significant sink of C. **Figure 1** shows the changes in the total C stock in living biomass (aboveground and belowground) across Europe between 1990 and 2020.

Region	1990	2000	2005	2010	2015	2020	Annual change 1990-2020		Annual change 2010-2020	
	Mt C						Mt C	%	Mt C	%
North Europe	2 576	2 768	2 935	3 087	3 296	3 397	+27.4	+0.93	+31.0	+0.96
Central-West Europe	2 411	2 761	2 962	3 115	3 294	3 470	+35.3	+1.22	+35.5	+1.08
Central-East Europe	2 183	2 640	2 833	3 150	3 708	3 905	+57.4	+1.96	+75.5	+2.17
South-West Europe	-	-	-	-	-	-	-	-	-	-
South-East Europe	858	949	1 026	1 092	1 179	1 225	+12.2	+1.19	+13.3	+1.16
EU-28	6 207	6 867	7 300	7 784	8 619	8 983	+92.5	+1.24	+119.9	+1.44
Europe	8 028	9 118	9 756	10 445	11 476	11 997	+132.3	+1.35	+155.2	+1.40

Figure 1. Changes in total C stock in living biomass (aboveground and belowground) in Europe (Forest Europe, 2020).

Besides stocking C within the ecosystem, forests contribute to climate change mitigation by providing wood that can be used for **long life-cycle products** as well as **energy (heat and/or electricity) generation** (EASAC, 2017).

Using wood along the forest supply chain should be based on the concept of **"cascading"**, which implies the priority use of wood material based on the higher added values that can be generated along the chain, and the use of wood for energy is typically the least valuable option (Ciccarese et al., 2014). Camia et al. (2021) found that about 50% of wood used for bioenergy in the EU comes from forest-based industry by-products and recovered post-consumer wood; 17% comes from tree tops, branches, and other residues, and 20% comes from small stems thinning wood (mainly from coppices) and harvested stems of poor quality that cannot be used in sawmills or for pulp and paper production.

Long life-cycle wood products include commodities like furniture, doors, flooring, packaging, paper products, or others (Canals Revilla et al., 2014) and represent a valid strategy to extend C stock outside the forests (Perone et al., 2015).

These products can **stock C for long periods of time**, delaying its emission into the atmosphere, according to the product's lifetime and decay process (UNECE/FAO, 2008; Bowyer et al., 2010). Giving the **long C turnover**, wood products highly contribute to climate change mitigation, by substituting traditional C-intensive materials (e.g., cement, iron, steel, and plastic), whose production causes high CO_2 emissions into the atmosphere (Sathre and O'Connor, 2010). Cement manufacturing and steel manufacturing, for example, account for 6% and 8% of the world's C emissions, respectively (The Economist, 2019). Early estimates indicated that, at the global scale, a shifting towards more wood products in building construction could reduce C emissions by as much as $6.6 \cdot 10^7$ $t \cdot yr^{-1}$ C and increase the long-term C stock by as much as $1.5 \cdot 10^7$ $t \cdot yr^{-1}$ C (Buchanan and Levine, 1999).

The role of wood products in climate change mitigation was recognized only recently by the Kyoto Protocol. The first commitment period (2008–2012) was based on the extremely simplified assumption that the mass of C in the wood is oxidized when biomass is collected. Actually, wood products may act as a C sink or C source, according to the balance between C inflow and outflow, and the corresponding C stock change. Therefore, starting from the second commitment period of the Kyoto Protocol (2013–2020), and in the context of the current **EU regulation 2018/841 for LULUCF** (Grassi et al., 2018; Nabuurs et al., 2018), the inclusion of **C accounting procedures** also for wood products is mandatory (Pilli et al., 2015).

Different approaches exist for C accounting in wood products. The recent 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol[4] defined the methods to be used according to the level of detail and the accuracy of the available data (Pilli et al., 2015).

When wood is used for **heat and/or electricity production**, the sequestered C is released into the atmosphere almost immediately. However, compared to fossil fuels, the combustion of wood causes more C release into the atmosphere per unit of delivered heat or electricity, since wood is characterized by a lower energy density and conversion efficiency (Agostini et al., 2014; Soimakallio et al., 2016; EASAC, 2017; Norton et al., 2019; IEA Bioenergy Task 45, 2021).

Despite this, it is important to recognize that the released C during wood combustion is part of the **short-term C cycle**; as long as wood collection does not exceed forest C sequestration, the atmospheric C concentration does not increase, since the emitted C was previously taken up from the atmosphere by felled trees and it will be sequestered again by the regrowth of trees over time in the harvested stand or by the growth of trees in other stands which act as C sink (**biogenic C**). As a result, the degradation of wood does not cause **additional C emissions** into the atmosphere and contribute to climate change mitigation.

In contrast, combustion of fossil fuels causes a linear flow of C from the geological stores (in which C was locked up for millions of years) to the atmosphere (IEA Bioenergy Task 45, 2021) (**Figure 2**). Therefore, the use of wood for energy generation can be considered to be **"carbon neutral"**, and it can support energy systems transformation to achieve carbon neutrality. Wood can be considered as a **"renewable resource"** as long as collection does not exceed increment and the productivity of the forest is maintained, according to the **SFM principles** (IEA Bioenergy Task 45, 2021)[5].

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4 https://www.ipcc-nggip.iges.or.jp/public/kpsg/pdf/KP_Supplement_Entire_Report.pdf

5 Biomass coming from permanent deforestation should not be recognized as renewable, so provisions are needed to exclude such cases from support, both for domestic applications, and for international trade.

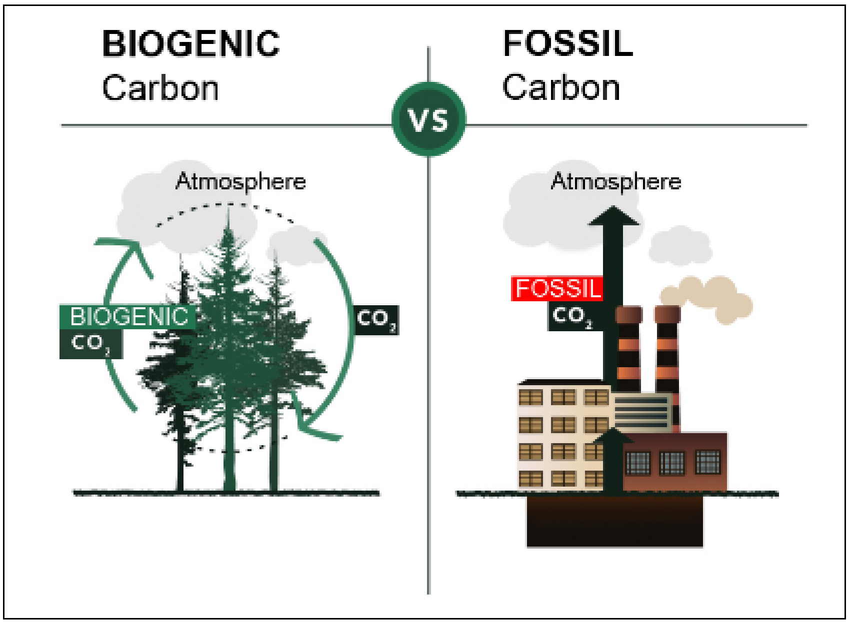

Figure 2. Difference between biogenic C and fossil C. The Intergovernmental Panel on Climate Change (IPCC) distinguishes between the "slow domain" of C (turnover times higher than 10000 years) and the "fast domain" of C related to vegetation and soil (turnover times of 1-100 and 10-500 years, respectively). Fossil fuel use transfers C from the slow to the fast domain, whereas bioenergy systems operate within the fast domain. (Source https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/).

Advantages and limitations related to the use of wood for energy are still **strongly debated** by the scientific community and the stakeholders. The concept of **"carbon neutrality"** gave a strong boost to the EU policies, with the aim of increasing the use of forest biomass as a source of bioenergy to substitute fossil fuel-based energy (EASAC, 2017; Norton et al., 2019). This led to the inclusion of forest biomass in the European Commission's definition of renewable energy in the **"2009 Renewable Energy Directive"** (RED)[6], being treated as "part of the package of measures required to reduce GHGs emissions" (Norton et al., 2019).

However, several authors recognized that the concept of "carbon neutrality" is **highly simplistic** for different reasons. First of all, wood collection immediately reduces forest C stock in biomass and soil (Routa et al., 2011) compared to no (or less) collection; moreover, the initial increase of atmospheric C concentration due to the combustion of wood instead of fossil fuels causes an increase of the **radiative forcing**, contributing to the **global warming**; this causes an **opposite effect** to that expected from renewable energies (Norton et al., 2019), which is reversed only if and when forest biomass regrows and reabsorbs C.

The required time to reabsorb the C emissions (i.e., payback period) may take from years to centuries, according to the type of biomass. If energy is produced by using **logging residues**, which otherwise

[6] Directive 2009/28/EC. https://www.eea.europa.eu/policy-documents/2009-28-ec

would remain in the forest and decompose quickly, there could be an overall **beneficial climate effect** if this biomass substitutes fossil fuels, and the corresponding payback period can be of the order of years (EASAC, 2017; Norton et al., 2019). On the contrary, if **trees with a large ongoing C stock** potential are harvested, the emissions from wood combustion are associated with a loss of forest C sink and, as a result, the net effect on the climate is negative (Smyth et al., 2016; Soimakallio et al., 2016). In this case, the payback period can reach **decades or centuries**, according to tree species and regrowth conditions (McKechnie et al., 2011; Ter-Mikaelian et al., 2015; Nabuurs et al., 2017; Searchinger et al., 2018; Norton et al., 2019).

Moreover, when using wood for energy, **fossil fuels inputs** are required for **wood harvesting, processing, storage, and transport** (Cherubini et al., 2009; Routa et al., 2011; EASAC, 2017; IEA Bioenergy Task 45, 2021). Despite these inputs are generally a small fraction of the energy content of the bioenergy products (Routa et al., 2011), all of them should be considered to assess the overall climate benefits related to the use of biomass instead of fossil fuels.

Therefore, the concept of "carbon neutrality" is **highly time and context dependent** and must be considered **case-by-case** by taking into account the type of biomass and the corresponding payback period, as well as all the CO_2 emissions that occur within the supply chain (EASAC, 2017; Norton et al., 2019).

When **climate change mitigation policies** were developed, the delay between the initial C emissions from wood combustion and the subsequent C compensation through trees' growth was not considered in the regulations. The **Paris Agreement** now commits *"to pursue efforts to limit the temperature increase even further to 1.5°C"*[7]; since according to the IPCC (2018) the average surface temperatures are likely to exceed 1.5°C between 2030 and 2052 on current trends, payback periods of decades or century increase the risk of overshooting the Paris Agreement targets (Norton et al., 2019).

It is therefore crucial to establish **governance systems** to ensure **best practices** based on the use of wood biomass characterized by payback periods compatible with the Paris Agreement targets, such as **logging residues from forest management**, wood from forests characterized by dieback, high fire risk, and natural disturbances in general (Norton et al., 2019).

Quantifying **forest wood** and **C stock** is crucial to define the effective environmental management practices and to support the decision-making processes. This is particularly important for the **local scale**, and especially for mountainous areas, where forests are an essential part of the ecosystems and heavily contribute to the local economy.

[7] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

In Italy, forests are generally managed though the **“Forest Management Plans”** (FMP). The basic management unit of each Plan is the **forest stand**, defined as an aggregation of trees over a specific area and sufficiently uniform in terms of species composition, structure and soil conditions, to be distinguished from other aggregations on adjacent areas. For each stand, the FMP defines the silvicultural treatments to carry out over a given period of time, while maintaining the productive, environmental, naturalistic, and social functions. For each stand, the quantitative data that is always made available is the total merchantable stem volume; more specific data, such as the number of trees, the volume of each tree, the average diameter, or the basal area, are not always made available.

Under these conditions, using models based on single-tree level data is not always possible, and the **only feasible solution** is to use **stand-level models**.

When planning **wood collection** for long life-cycle products rather than for energy generation, it is also crucial to provide the stakeholders (e.g., supply chain operators and local administrations) with **models** able to support them in selecting the **most suitable machines to use**. This is essential to make forestry operations more productive and efficient, while increasing the safety of forest workers and reducing their physical stress. In many cases, the selection of the most suitable machines is still based on the experience and intuition of forest workers and technicians, and often does not consider **possible changes in the long term**, such as the development of new machines and technologies, as well as the improvement of the road network (Kühmaier and Stampfer, 2010). Nevertheless, other **environmental, economic, and social factors** should also be considered, such as: (i) characteristics of the stands (Stampfer et al., 2003), (ii) characteristics of the forest roads, extraction distance and soil conditions (Stampfer and Steinmueller, 2004; Stampfer et al., 2010; Monarca et al., 2011), (iii) harvesting method and level of mechanization (Proto et al., 2017) and (iv) climate.

At the same time, it is necessary to provide the stakeholders with information on the **costs of the operations**, which considerably affect the economic sustainability of the whole supply chain.

Several **models** were developed over time to support user’s decision. In some of these models, the types of usable machines are not provided as an output, but have to be defined by the user as an input data, through which the economic costs are subsequently calculated; other models allow the calculation of the cost only for a single operation and not for the whole forestry machinery chain (FMC). Again, in other cases, the models suggest the most suitable types of machines only according to few technical parameters, e.g., harvested volume or average slope.

It is possible to conclude that there is still a **lack of generalized approach** to select the most suitable forestry machines for wood collection computing, at the same time, the economic costs of the **whole FMC**.

1.2 Aims of the PhD Thesis

The aims of the PhD Thesis are different and related to the previously described topics.

As it concerns the **first topic** (**assessment of forest wood and C stock**) the aim is to develop a model based on FMPs data in order to:

- calculate the mass of wood ($t \cdot yr^{-1}$ dry matter, DM) and C ($t \cdot yr^{-1}$ C) at the stand level in the following ecosystem compartments:
    - aboveground wood biomass;
    - belowground wood biomass;
    - dead organic matter;
- estimate the potentially available mass of logging residues (i.e., branches and tops; $t \cdot yr^{-1}$ DM) for energy generation and the corresponding potentially generated energy ($GJ \cdot yr^{-1}$) under the hypothesis that this biomass replaces non-renewable energy sources.

This allows to provide local administrations and public decision-makers with useful information to update FMPs and to address forest management. This is also useful to define the contribution of local forests to the bioenergy supply chain, reducing the provision of wood on foreign markets.

As it concerns the second topic (**forestry mechanization**), the aim is to develop an innovative approach in order to:

- select the most suitable FMC to adopt at the stand level for wood collection (harvesting and transport), according to the forestry and operating conditions;
- compute the economic costs ($€ \cdot h^{-1}$; $€ \cdot t^{-1}$ DM; €) of the selected FMC.

This allows to support local administrations and supply chain operators (e.g., logging companies) in awarding public grants/subsidies and setting transparent operations tariffs, respectively.

1.3 Structure of the PhD Thesis

The PhD Thesis is based on two activities. The **activity n. 1** (related to the topic n. 1) is described in chapters 2, 3, 4 and 5. The **activity n. 2** (related to the topic n. 2) is described in chapter 6. The activity n. 1 was carried out by taking the Valle Camonica District (Lombardy Region, Italy) as Case Study Area.

Chapter 2 describes the first version of the empirical MS Office Excel-based model **WOody biomass and Carbon ASessment (WOCAS v1)**. The model estimates the mass of C ($t \cdot yr^{-1}$ C) in: (i) aboveground wood biomass, (ii) belowground wood biomass, (iii) deadwood and (iv) litter at the stand level in a predefined reference year. It also gives the possibility to analyze future scenarios based on the continuation of the current management practices rather than improved practices, to define a possible mitigation strategy at the local level for the activation of a Voluntary Carbon Market.

In this first version of the model, calculations were performed by using the gross annual increment provided by the FMPs. The annual merchantable stem mass was computed without considering mortality due to self-thinning and natural disturbances; the mass of C in deadwood and litter was calculated by using linear equations also applied at the regional and national level for C stock accounting within the UNFCCC. The model was firstly tested on a dataset of **2019 public stands** extracted from **45 FMPs (forest area: 37000 ha)** for the period **1984-2016**, and preliminary results were presented. Starting from this analysis, calculations were performed to define a first possible **mitigation strategy** to be realized for the period **2017-2029**, based on the conversion of coppices to high forests.

WOCAS v1 was improved into a second version **(WOCAS v2)**, and the main **improvements** were (**chapter 3**): (i) calculation of the gross annual increment of the stand through a **theoretical non-linear growth function** based on the merchantable stem mass, without considering the age; (ii) inclusion of mortality due to self-thinning and natural disturbances in the calculation; (iii) quantification of the annual dead organic matter mass according to the annual inputs (self-thinning, natural disturbances, logging residues) and output (decomposition). The improved methodology was applied to the same dataset used for WOCAS v1 (i.e., 2019 forest stands, 45 FMPs; forest area: 37000 ha; period: 1984-2016).

Moreover, an **innovative methodology** was implemented into WOCAS v2 to calculate the mass of **potentially available residues** at the stand level ($t \cdot yr^{-1}$ DM) for energy generation, the potentially generated heat and electricity ($GJ \cdot yr^{-1}$) and the potentially avoided CO_2 emissions into the atmosphere related to the final combustion process ($t \cdot yr^{-1}$ CO_2), under the hypothesis that wood substitutes non-renewable energy sources. This methodology is presented in **chapter 4**. The mass of potentially available residues is computed by multiplying the mass of potentially producible residues for a recovery rate based on six availability factors (i.e.: stand's function, stand's management system, harvesting method, stand's accessibility, forest roads' transitability and energy market demand). The methodology was applied to **1215 stands** of the Case Study Area for the period **1994-2016**; in this first application, only the stand's function and the stand's management system were considered, since no data on the other factors were made available for each stand at the time of the study.

In **chapter 5**, the calculation of the potentially available residues was improved by also considering the stand's accessibility, the forest roads' transitability and the energy market demand. FMPs data coming from WOCAS v2 were combined with a **Digital Elevation Model (DEM)** in **Geographic Information System (GIS) software** and data on the topographic features, landscape morphology and characteristics of the forest roads were collected. The georeferenced stands were characterized by both single contiguous areas (i.e., single stands), as well as different non-contiguous areas (i.e., sub-stands). Overall, **2157 polygons** – consisting of both single and sub-stands – were analyzed, covering the period **2009-2016**.

Chapter 6 is subdivided into two parts. The first one describes the first version of the stand-level model **"FOREstry MAchinery chain selection" (FOREMA v1)**. The model defines the feasible FMC that can be adopted for wood collection, by combining the categories that compose **seven technical parameters** that characterize the stand: (i) management system, (ii) wood assortment, (iii) harvesting method, (iv) level of mechanization, (v) forest roads' transitability, (vi) stand's accessibility, and (vii) harvested merchantable mass ($t \cdot ha^{-1}$ DM). For each FMC, FOREMA v1 defines the sequence of the operations and the types of machines that can be used.

The second part of the chapter is focused on the computation of the **economic costs** (€$\cdot h^{-1}$; €$\cdot t^{-1}$ DM; €) of the selected FMC, by quantifying, for each operation, fixed and variable costs. The proposed approach was applied for a Case Study concerning the collection of **woodchips** from a coppice stand in the Italian Alps for **energy generation**.

Finally, **chapter 7** outlines the general conclusions and the main future perspectives of the work.

The **contributions** of Luca Nonini to the **chapters** of this PhD Thesis were the following:

- chapter 2: work planning with the co-author; data collection and elaboration; model development; writing with input from the co-author;
- chapter 3: work planning with the co-author; data collection and elaboration; model improvement; writing with input from the co-author;
- chapter 4: work planning with the co-author; data collection and elaboration; writing with input from the co-author;
- chapter 5: work planning, data collection and elaboration with the co-authors; writing with the co-authors;
- chapter 6: work planning with the co-author; data collection and elaboration; model development with input from the co-author; writing with input from the co-author.

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Chapter 2 – Estimation of carbon storage of forest biomass for voluntary carbon markets: preliminary results

Slightly modified from: **Nonini L.**, Fiala M. (2019). Estimation of carbon storage of forest biomass for voluntary carbon markets: preliminary results. Journal of Forestry Research. https://doi.org/10.1007/s11676-019-01074-w

Abstract: Estimating the carbon storage of forests is essential to support climate change mitigation and promote the transition into a low-carbon emission economy. To achieve this goal, voluntary carbon markets (VCMs) are essential. VCMs are promoted by a spontaneous demand, not imposed by binding targets, as the regulated ones. In Italy, only in Veneto and Piedmont Regions (Northern Italy), VCMs through forestry activities were carried out. Valle Camonica District (Northern Italy, Lombardy Region) is ready for a local VCM, but carbon storage of its forests was never estimated. The aim of this work was to estimate the total carbon storage (TCS; t C·ha^{-1}) of forest biomass of Valle Camonica District, at the stand level, taking into account: (1) aboveground biomass, (2) belowground biomass, (3) deadwood, and (4) litter. A user-friendly model, based on site-specific primary (measured) data, was developed and applied to a dataset of 2019 stands extracted from 45 Forest Management Plans (FMPs). Preliminary results showed that, in 2016, the TCS achieved 76.02 t C·ha^{-1}. The aboveground biomass was the most relevant carbon pool (48.86 t C·ha^{-1}; 64.27% of TCS). From 2017 to 2029, through multifunctional forest management, the TCS could increase of 2.48 t C·ha^{-1} (+3.26%). In the same period, assuming to convert coppices stands to high forests, an additional TCS of 0.78 t C·ha^{-1} (equal to 2.85 t CO_2·ha^{-1}) in the aboveground biomass could be achieved without increasing forest areas. The additional carbon could be certified and exchanged on a VCM, contributing to climate change mitigation at a local level.

Keywords: carbon storage assessment; forest management plan; site-specific primary data; voluntary carbon market; climate change mitigation.

List of the parameters in the Text

Definition	Symbol	Unit
Multiplicative coefficient of the gross annual increment	k_I	-
Biomass expansion factor	k_1	-
Wood basic density	k_2	t·m^{-3} of dry matter, DM
Root-shoot ratio	k_3	-
Deadwood biomass expansion factor	k_4	-
Carbon fraction of aboveground wood biomass DM	k_5	-
Carbon fraction of belowground wood biomass DM	k_6	-
Carbon fraction of deadwood DM	k_7	-

2.1 Introduction

Forests store about 45% of the total Earth's carbon (Bonan, 2008) and their role in climate change mitigation is widely recognized (Masera et al., 2003; IPPC, 2006; Nabuurs et al., 2008; Calfapietra et al., 2015; Ekholm, 2016; Gren and Zeleke, 2016).

"Mitigation" refers to both the increase of carbon storage of the biosphere, compared to a business as usual (BAU) situation, and the reduction of carbon emissions into the atmosphere due to anthropogenic activities (Hoberg et al., 2016). The concept of "mitigation" is strongly linked to the concept of "abatement" (Rutherford and Weber, 2017). Forest carbon storage depends on forest biomass dynamics and it is defined as the product of forest biomass and its carbon content factor (Zeng et al., 2018).

In the context of the current climate change, carbon storage assessment is one of the most important goals of forest management, because it is directly linked to fuels and bioenergy assessment (Affleck, 2019). Anthropogenic activities can both reduce (e.g., through deforestation or land use change) or enhance (e.g., through sustainable forest management, afforestation, and reforestation) forest carbon storage (IPPC, 2006; Eriksson et al., 2007; Jandl et al., 2015; Noormets et al., 2015).

To limit the problem of anthropogenic greenhouse gases (GHG) emissions into the atmosphere, many international agreements were introduced over time. According to the United Nations Framework Convention on Climate Change (UNFCCC), it is essential to achieve a *"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner"* (UNFCCC, 1992).

The main implementing instrument of the UNFCCC is the Kyoto Protocol (KP), adopted in 1997 and came into force in 2005. The KP gave rise to an institutional carbon credits (CC) market, by setting, for the industrialized countries included in the Annex I of the Convention, binding targets regarding the emissions of different GHGs (de Alegría et al., 2017; Raufer et al., 2017). Annually, each country listed in this Annex has to produce a National Inventory Report (NIR) of its GHGs emissions and removals, by taking into account sources and sinks of five sectors. One of them concerns land use, land use change and forestry activities (LULUCF) (Federici et al., 2008; de Alegría et al., 2017). Recently, the key role of forests in climate change mitigation was also recognized by the Paris Agreement (November 4th, 2016), which defined the need to maintain the global temperature increase below 2 °C compared to the pre-industrial period, and the EU regulation 2018/841 for LULUCF. The introduction of a Forest Reference Level (FRL) to use for the accounting, and the inclusion of

accounting procedures also for Harvested Wood Products (HWP), are the most innovative aspects of the EU regulation (Grassi et al., 2018; Nabuurs et al., 2018).
In addition to the regulated CC markets, also voluntary carbon markets (VCM) are widespread all over the world. VCMs are promoted by a spontaneous demand, not imposed by binding targets, as the regulated ones. Buyers are generally public or private companies, non-profit organizations or individual citizens that want to mitigate the GHGs emissions caused by their activities or linked with the production of environmentally impacting goods (products and/or services). Sellers are forest owners and managers whose activities promote CC generation. In the recent years, VCMs were characterized by a phase of strong expansion – both in terms of the number of operators and the quantities of CC traded – that led to an easier access and a greater flexibility, mainly due to the absence of a specific legislation and simpler procedures for CC exchange. In the context of VCMs, forestry activities that can produce CC are: (1) afforestation, reforestation, and urban forestry, (2) reduction of GHGs emissions from deforestation and forest degradation (REDD), (3) use of renewable energy, and (4) improved forest management (IFM) systems (Kollmuss et al., 2008; Gorte and Ramseur, 2010; Arnoldus and Bymolt, 2011; Merger and Pistorius, 2011; Vacchiano et al., 2018).
Often, in mountainous ecosystems, forest area is high, and it is not possible to enhance further the carbon storage by afforestation or reforestation activities. In this case, the carbon storage can be enhanced only through IFM systems, that include different practices, mainly referred to: (1) extension of the rotation length, (2) reduction of woody biomass harvesting compared to the maximum volume allowed by the forest management plans (FMP), (3) conversion of aged and/or abandoned coppices to high forests, (4) increase of carbon retention in HWPs, (5) increase of the use of HWPs instead of more fossil-energy intensive materials, and (6) increase of the use of woody biofuels to substitute fossil fuels (Aruga et al., 2013; Alberdi et al., 2016; Ruiz-Peinado et al., 2017; Vacchiano et al., 2018).
Each CC exchanged on a VCM promotes the mitigation of 1 t of CO_2 released into the atmosphere from anthropogenic activities. Moreover, CCs from IFM systems are important to address sustainable forest management for both public and private owners (Vacchiano et al., 2018).
Processes of GHGs emissions and storage in forests through VCMs were analyzed also in Italy, but only in Veneto and Piedmont Regions (Northern Italy) VCMs through forestry activities were carried out through the LIFE07 ENV/IT/000388 Project "Carbomark" (Carbomark Project, 2011) and the "Carbon Technical Table" – funded by the Piedmont Region (Piedmont Region, 2017).
Valle Camonica District (Northern Italy, Lombardy Region) is ready for a VCM, because there are: (1) extensive forest areas and many data collected in the FMPs, (2) many manufacturing activities, potentially interested in taking part in a local VCM, and (3) a well-developed economy. Despite this, the carbon storage of Valle Camonica forests was never estimated.

The first step to promote a local VCM is to collect information about: (1) the amount of carbon currently stored in forests and (2) the amount of carbon that could be stored in the future maintaining the current forest management practices (case 1) or assuming the conversion of aged and/or abandoned coppices to high forests (case 2).
The aim of this work was to estimate the total carbon storage (TCS; t $C \cdot ha^{-1}$) of Valle Camonica forest biomass, at the stand level, to support a local VCM. A user-friendly model called WOody biomass and Carbon ASessment (WOCAS v1) was developed and applied to a dataset of 2019 stands extracted from 45 FMPs. The model calculates the TCS in the year 2016 and allows the analysis of future changing of the TCS considering both the current management practices as well as the conversion of coppices to high forests.

2.2 Materials and methods

The model allows the estimation of the TCS (t $C \cdot ha^{-1}$) of public forests (soil excluded) at the stand level. It was developed through MS Office Excel and it is made up of two spreadsheets: (1) parameters selection and (2) carbon storage assessment.
The first one contains a table in which the user defines different classification criteria, combining the following three sub-criteria (SC) (Del Favero, 2002):

- SC_1: forest structure;
- SC_2: forest function;
- SC_3: forest typology and variants.

A sub-code is assigned to each SC and the combination of these sub-codes generates a unique code (classification criteria code), by which proper calculation parameters are selected and uploaded within the second spreadsheet.
This one consists of a database where each forest stand (j) represents a record, organized in several fields containing specific input data. For each j-stand, the required input data are:

- starting ($YR_{S(j)}$) and deadline ($YR_{D(j)}$) year of the FMP;
- forest structure;
- forest function;
- forest typology and variants;
- area ($A_{(j)}$; ha);
- growing stock volume ($GSV_{(j)}$; $m^3 \cdot ha^{-1}$) at $YR_{S(j)}$;

- gross annual increment of GSV ($GAI_{n(j)}$; $m^3 \cdot ha^{-1} \cdot yr^{-1}$) at $YR_{S(j)}$;
- harvested GSV over time ($H_{n(j)}$; $m^3 \cdot ha^{-1} \cdot yr^{-1}$);

$GSV_{(j)}$ is referred to the volume of all living stems excluding all branches and foliage. The model firstly defines the state of the forests (in terms of TCS; t $C \cdot ha^{-1}$) at the starting year of the simulation and, therefore, it allows the analysis of three management Scenarios (S):

- S_1: BAU_F (future business as usual), to estimate the TCS at the deadline year of the most recent FMP, simply due to woody biomass harvesting, on the hypothesis that there is no variation of the current forest management over time. In other words, S_1 represents the most probable future management in the absence of IFM systems;

- S_2: SST_P (past sustainable), based on the conversion of coppices to high forests. In other words, this Scenario allows to estimate the TCS at the starting year of the simulation on the hypothesis that the conversion was also introduced in the past;

- S_3: SST_F (future sustainable), identical to S_1 but based on the conversion of coppices to high forests applied since the starting year of the simulation.

For the purposes of VCMs, it is necessary to estimate the additional carbon ($S_3 - S_1$) that can be stored in the aboveground woody biomass.
In the parameters selection spreadsheet, the user defines a multiplicative coefficient (k_I) of the $GAI_{n(j)}$ ($k_I > 0$) for each classification criteria code, so that the gross annual increment associated to each j-stand ($GAI^*_{n(j)}$; $m^3 \cdot ha^{-1} \cdot yr^{-1}$) is calculated as:

$$GAI^*_{n(j)} = k_I \cdot GAI_{n(j)} \qquad \text{(Eq. 1)}$$

This coefficient is introduced to make the model more flexible, allowing the user to choose – at the beginning of the simulation – which gross annual increment to use for each j-stand. In particular, by setting $k_I = 1$, calculations are performed by using the gross annual increment reported in the FMPs, whereas with $k_I \neq 1$ calculations are performed with higher or lower values of the increment reported in the Plans, for example to simulate a faster ($k > 1$) or a slower ($k < 1$) growth, i.e., for possible accounting of the effect of climate change (see Case study for the details about the k_I values used in the study). In any case, the gross annual increment is defined at the beginning of the simulation and

does not change over time. Since the increment varies according to stands' age and growing stock, forest management practices and environmental conditions, this may represent a quite strong assumption.
To define the state of the forests at the starting year of the simulation, as well as for the S_1, S_2 and S_3 scenarios, the growing stock volume for the year n ($GSV_{n(j)}$; $m^3 \cdot ha^{-1}$) is calculated, for each j-stand, through a "gain-loss balance", starting from the GSV of the previous year ($GSV_{n-1(j)}$; $m^3 \cdot ha^{-1}$), adding the gross annual increment as previously defined ($GAI^*_{n(j)}$; $m^3 \cdot ha^{-1} \cdot yr^{-1}$) and subtracting losses due to harvesting (if any) in the year n ($H_{n(j)}$; $m^3 \cdot ha^{-1} \cdot yr^{-1}$):

$$GSV_{n(j)} = GSV_{n-1(j)} + GAI^*_{n(j)} - H_{n(j)} \qquad \text{(Eq. 2)}$$

To define the TCS ($t\ C \cdot ha^{-1}$) at the starting year of the simulation, $H_{n(j)}$ values come directly from the FMPs (primary data), whereas in the case of S_1, S_3 and, eventually, S_2, values are calculated according to: (1) harvesting intensity (k_H), and (2) harvesting year (YR_H). k_H expresses the percentage of $GAI^*_{n(j)}$ that is harvested in the year under analysis (k_H = % $GAI^*_{n(j)}$).
As a result, for each Scenario, $H_{n(j)}$ ($m^3 \cdot ha^{-1} \cdot yr^{-1}$) is calculated as follows:

$$H_{n(j)} = GAI^*_{n(j)} \cdot k_H \qquad \text{(Eq. 3)}$$

The harvesting year (YR_H) is defined by the user in the carbon storage assessment spreadsheet for each j-stand.
According to the IPCC Guidelines (IPCC, 2006) forest carbon storage should be assessed in:

- living biomass (aboveground and belowground);
- dead organic matter (deadwood and litter);
- soil.

The model estimates the total carbon storage ($TCS_{TB(j)}$; $t\ C \cdot ha^{-1}$) in (Table 1):

- aboveground wood biomass ($TCS_{AB(j)}$; $t\ C \cdot ha^{-1}$);
- belowground wood biomass ($TCS_{BB(j)}$; $t\ C \cdot ha^{-1}$);
- deadwood ($TCS_{DW(j)}$; $t\ C \cdot ha^{-1}$);
- litter ($TCS_{LI(j)}$; $t\ C \cdot ha^{-1}$).

Table 1. Carbon pools taken into account by the model (modified from Federici et al., 2008).

N.	Name and definition
1	Aboveground wood biomass: over-bark living woody biomass above the soil surface. Stems and branches of all dimensions are included. Foliage is excluded.
2	Belowground wood biomass: all living woody biomass of coarse live roots (diameter > 2 mm). Fine roots (diameter < 2 mm) are included in the litter or in the soil organic matter because they cannot be empirically distinguished from them.
3	Deadwood: all non-living woody biomass not contained in the litter, both standing and lying on the soil surface, with diameter ≥ 10 cm.
4	Litter: all non-living woody biomass with diameter < 10 cm. It includes woody biomass in different stages of decomposition above the mineral or organic soil and fine roots.

As well as for the litter, literature reports relations between aboveground and soil carbon storage (Federici et al. 2008), but since the uncertainty of the estimation is very high, the soil is not included in the calculations. The TCS is estimated as a function of $GSV_{n(j)}$ ($m^3 \cdot ha^{-1}$) (Federici et al., 2008):

$$TCS_{AB(j)} = GSV_{n(j)} \cdot k_1 \cdot k_2 \cdot k_5 \quad \text{(Eq. 4)}$$

$$TCS_{BB(j)} = GSV_{n(j)} \cdot k_2 \cdot k_3 \cdot k_6 \quad \text{(Eq. 5)}$$

$$TCS_{DW(j)} = GSV_{n(j)} \cdot k_1 \cdot k_2 \cdot k_4 \cdot k_7 \quad \text{(Eq. 6)}$$

where:

$TCS_{AB(j)}$ is TCS of aboveground wood biomass ($t\ C \cdot ha^{-1}$);

$TCS_{BB(j)}$ is TCS of belowground wood biomass ($t\ C \cdot ha^{-1}$);

$TCS_{DW(j)}$ is TCS of deadwood ($t\ C \cdot ha^{-1}$);

$GSV_{n(j)}$ is growing stock volume of the j-stand for the year n ($m^3 \cdot ha^{-1}$);

k_1 is biomass expansion factor (aboveground wood biomass volume on growing stock volume);

k_2 is wood basic density, ratio between wood dry matter and wood fresh volume ($t \cdot m^{-3}$ of dry matter, hereafter DM);

k_3 is root-shoot ratio (belowground wood biomass dry matter on growing stock biomass DM);

k_4 is deadwood biomass expansion factor (deadwood DM on aboveground wood biomass DM);

k_5 is carbon fraction of aboveground wood biomass DM;

k_6 is carbon fraction of belowground wood biomass DM;

k_7 is carbon fraction of deadwood DM.

The TCS of litter wood biomass ($TCS_{LI(j)}$; $t\ C \cdot ha^{-1}$) is computed by applying linear equations to the

TCS of aboveground wood biomass (Federici et al., 2008):

Coniferous stands: $\mathrm{TCS_{LI(j)}} = \left(0.0659 \cdot \mathrm{TCS_{AB(j)}}\right) + 1.5045$ (Eq. 7)

Broadleaves stands: $\mathrm{TCS_{LI(j)}} = (-0.0299 \cdot \mathrm{TCS_{AB(j)}}) + 9.3665$ (Eq. 8)

Rupicolous stands: $\mathrm{TCS_{LI(j)}} = (-0.0165 \cdot \mathrm{TCS_{AB(j)}}) + 7.3285$ (Eq. 9)

The user defines k_1, k_2, k_3, k_4, k_5, k_6, k_7 values in the parameters selection spreadsheet. The TCS of the living wood biomass is:

$$\mathrm{TCS_{LB(j)}} = \mathrm{TCS_{AB(j)}} + \mathrm{TCS_{BB(j)}} \quad \text{(Eq. 10)}$$

The TCS of the dead organic matter is:

$$\mathrm{TCS_{DOM(j)}} = \mathrm{TCS_{DW(j)}} + \mathrm{TCS_{LI(j)}} \quad \text{(Eq. 11)}$$

As a result, the TCS of each j-stand is:

$$\mathrm{TCS_{TB(j)}} = \mathrm{TCS_{LB(j)}} + \mathrm{TCS_{DOM(j)}} \quad \text{(Eq. 12)}$$

2.3 Case Study

The model was applied to the Valle Camonica District to estimate, for the first time, the TCS related to public forests (Figure 1). The total forest area of the District is $6.5 \cdot 10^4$ ha, approximately 52% of the total area; $4.2 \cdot 10^4$ ha, approximately 64%, are public (managed through FMPs), whereas the remaining $2.3 \cdot 10^4$ ha are private (not managed through FMPs). In the eastern side of the District, the Adamello Regional Park covers one third of the total area of the District ($5 \cdot 10^4$ ha, approximately, in 19 municipalities of the Province of Brescia). Forests mainly consist of coniferous (especially *Picea abies* L. and *Larix decidua* Mill., in an amount equal to 30% and 20%, respectively) and, to a lesser extent, broadleaves (mainly *Alnus viridis chaix* D.C. and *Castanea sativa* Mill., 11% and 8%, respectively). Taking into account the prevailing function, forests with production function cover about 60% of the total forest area, followed by forests with protection (38%) and recreational function (2%).

Figure 1. Studied Area (Source: https://www.google.it/maps).

Data related to 2019 forest stands were extracted from 45 FMPs collected in the Cadastral FMPs database (CPA v2) made available by the Mountain Community. The area of these stands is very heterogeneous, as shown in Table 2.

Table 2. Area of the stands extracted from the CPA v2.

	Area (ha)				
	Total	Average	SD	Min	Max
All stands	$3.67 \cdot 10^4$	18.2	10.9	0.8	110.0
Coppices	$5.52 \cdot 10^3$	16.1	11.1	0.8	96.0
High forests	$3.12 \cdot 10^4$	18.6	10.8	1.3	110.0

SD is Standard deviation.

Stands located in the "Legnoli" and "Valle di Scalve" forests were not taken into account because no data were made available from the CPA v2. In these FMPs, $GSV_{(j)}$ is expressed as "gross cormometric volume" (volume of the stems over bark excluding tops with diameter d_T < 7 cm and all branches). If data on gross annual increment were not available from the CPA v2, values based on weighted averages and provided by literature (Del Favero, 2002) were used. $TCS_{DW(j)}$ was estimated by applying a value of $k_4 = 0.15$ for deciduous and $k_4 = 0.25$ for evergreen stands, according to Harmon et al. (2001). Moreover, specific values of k_5 were assumed, by taking into account the stem of the leading species (Thomas and Martin, 2012). If they were not available, general values of $k_5 = 0.508$ for coniferous and $k_5 = 0.477$ for broadleaves stands (Thomas and Martin, 2012) were adopted. It was also assumed that $k_5 = k_6 = k_7$.

To define the TCS (t $C \cdot ha^{-1}$) at the starting year of the simulation, the "gain-loss balance" was performed for 33 years, from 1984 (starting year of the oldest FMP) to 2016 (more recent data made available by the CPA v2). The k_I coefficient was set equal to 1 for each classification criteria code. S_I

Scenario (BAU_F, future business as usual) covered the time between 2017 and 2029 (deadline year of the most recent FMP). To estimate the TCS in 2029, according to the suggestions of the Mountain Community, different harvesting intensity (k_H; % $GAI^*_{n(j)}$), were defined according to the main function of the stands, and the following categories were considered:

- C1: coniferous stands with production function ($A_{C1} = 1.75 \cdot 10^4$ ha; 47.6% of the total area of all the stands, A_T). This category includes stands mainly managed for woody biomass supply. This function is clearly enhanced by stands of *P. abies* L. and, to a lesser extent, *Abies alba* Mill. and *L. decidua* Mill. The main goals of this type of management are: (1) the maximization of the owners' income, compatibly with the other ecosystem functions and (2) the increase of the supply of woody biomass for the strengthening of the local supply chain (mainly for building purposes and, to a lesser extent, for biomass-to-energy processes) maintaining or enhancing the growing stock volume over time (Ducoli, 2012). Considering that $GAI_{n(j)}$, by definition, includes the increment of living trees plus the increment of trees which died within the same period of time due to harvesting or natural turnover rate (this latter equal to 10% $GAI_{n(j)}$, approximately), for all the stands included in this category, it was assumed k_H = 90% $GAI^*_{n(j)}$. A more intensive management is justified only for specific needs related to phytosanitary defense and protection from natural disturbances. In fact, if in the short-term woody biomass harvesting can exceed the annual increment (i.e., for years characterized by a high demand of woody biomass), in the medium-long term this condition should never occur, in order to avoid the progressive depletion of the growing stock and of the stand's productivity.

- C2: coniferous, broadleaves (both coppices and high forests) and mixed forests stands with protection function ($A_{C2} = 1.25 \cdot 10^4$ ha; 34.0% of A_T). This category includes stands best suited for hydrogeological risk protection and regulation of meteoric water flows, as well as stands specifically assigned to the direct protection against avalanche, soil erosion and landslide, phytosanitary defense, and wildfire. Although the species in these areas are generally left to "natural evolution", the main goals are: (1) maintenance and/or improvement of the protection function of the stands, by planning interventions to monitor the safety conditions of the vegetation (e.g., elimination of unstable trees located in areas with high hydrogeological risk and enhancement of avalanche barriers), (2) limitation of the growth of invasive species, and (3) sanitary silvicultural treatments on degraded areas to reduce the risk of wildfires. For all the stands included in this category it was assumed k_H = 80% $GAI^*_{n(j)}$;

- C3: broadleaves and mixed forests stands with production function, stands with recreational function and damaged stands to be recovered ($A_{C3} = 3.56 \cdot 10^3$ ha; 9.7% of A_T). The mail goals for these stands concern: (1) the transition to an ordinary management and (2) the protection of the so-called *"targeted species"*. The first aspect mainly concerns stands of *C. sativa* Mill., characterized by high physiognomic-structural disorders. These stands generally derive from abandoned ancient fruit chestnut trees; the suckers are often stunted, twisted, and grow on little vigorous or rotting stumps. As a result, the forest cenosis is extremely simplified, and the growing stocks (and annual increments) are very low compared to that of actively managed coppices. Moreover, the presence of grazing and uncontrolled wildfires worsens these conditions. Currently, the management of these stands is occasional; restoration is slow and complex and therefore the transition to an ordinary management can be achieved only by promoting specific practices and by monitoring and preventing grazing and wildfires. The second aspect concerns the *"targeted species"* (*Acer pseudoplatanus* L., *Tilia cordata* Mill., *Ulmus glabra* Huds*., Ilex aquifolium* L*., Alnus glutinosa* L., and *Carpinus betulus* L.). These species generally colonize abandoned agricultural lands with high water availability and they strongly contribute to the biodiversity enhancement. Therefore, they need to be specifically protected through *"ad-hoc"* management practices including, in some cases, the strong limitation of their use. For all the stands included in this category it was assumed $k_H = 50\% \ GAI^*_{n(j)}$;

- C4: coppice stands with production function ($A_{C4} = 3.19 \cdot 10^3$ ha; 8.7% of A_T): these stands are generally managed for fuelwood production and are concentrated in the valley floor, where the main species are *C. sativa* Mill., *Fagus sylvatica* L., *Quercus robur* L. and *Quercus pubescens* Willd. As the altitude increases, coppices are generally supplanted by high forests. In any cases, the Forest Sector Plan of Valle Camonica, recently updated (November 2018), promotes the conversion of aged coppices (older than 40 years) to high forests. For all the stands included in this category, as well as for the C1 category, the main goal is to maximize the annual supply of local woody biomass (for energy purposes in this case) maintaining the growing stock volume constant over time. Therefore, for all the stands included in this category, it was assumed $k_H = 90\% \ GAI^*_{n(j)}$.

Also for this Scenario, the k_I coefficient was set equal to 1 for each classification criteria code. Regarding the harvesting year (YR_H), according to the suggestions of the Mountain Community, for each j-stand it was assumed to harvest wood each year from 2017 to 2029, under the hypothesis that the area of each stand does not change over time. S_2 Scenario (SST_P, past sustainable) was not considered because, for the purpose of CC generation, what is of interest are S_1 and S_3 Scenarios, as previously mentioned. For S_3 Scenario (SST_F, future sustainable), according to the suggestions of the Mountain Community, the changing in the TCS was evaluated by assuming to convert to high forests coppices of: (1) *F. sylvatica* L., (2) *Q. robur* L. and *Q. pubescens* Willd., (3) *C. sativa* Mill., (4) *Fraxinus ornus* L., and (5) *Ostrya carpinifolia* Scop. The analysis was performed under the hypothesis of converting to high forests not only the coppices already classified as "coppices under conversion", but also coppices with production and protection function, as well as damaged coppices to be recovered, because it could be an interesting strategy for the purpose of sustainable and multifunctional forest management of the District. For these stands, not having experimental data to work with, in this first version of the model it was assumed – as a first approximation – that the $GAI_{n(j)}$ was the same of that of the stands already managed as high forest. Thus, the ratio between the weighted average $GAI_{n(j)}$ of high forests stands and the weighted average $GAI_{n(j)}$ of coppices stands was computed and assigned to the k_I coefficient in the parameters selection spreadsheet. The following values of k_I were used:

- *F. sylvatica* L., *Q. robur* L., and *Q. pubescens* Willd.: $k_I = 1.75$;
- *C. sativa* Mill., *F. ornus* L., and *O. carpinifolia* Scop.: $k_I = 1$ (no differences between $GAI_{n(j)}$ of high forests and coppices stands were observed).

The $GAI^*_{n(j)}$ associated to each stand under conversion was quantified according to Eq. 1. For a preliminary estimation, for each stand under conversion, it was assumed that $k_H = 100\%$ $GAI^*_{n(j)}$, under the hypothesis of cutting the dominated trees and promoting the conversion to high forest of the suckers with the best characteristics. Finally, it was hypothesized to carry out two cuts: (1) $YR_{H1} = 2017$ and (2) $YR_{H2} = 2027$.

2.4 Results and discussion

2.4.1 State of the forest at the starting year of the simulation

In 2016, the total carbon storage of the public forest stands (total growing stock volume $GSV_F = 180.93\ m^3 \cdot ha^{-1}$) was $TCS_F = 76.02\ t\ C \cdot ha^{-1}$. Of this, the total aboveground carbon storage was $TCS_{AB\_F} = 64.27\%$, while the total belowground carbon storage was $TCS_{BB\_F} = 14.10\%$. The total deadwood carbon storage was $TCS_{DW\_F} = 14.36\%$, while the total litter carbon storage was $TCS_{LI\_F} = 7.27\%$. Taking into account the management system, the TCS of coppices (growing stock volume $GSV_{F1} = 93.42\ m^3 \cdot ha^{-1}$) was $TCS_{F1} = 53.93\ t\ C \cdot ha^{-1}$. Of this, $TCS_{AB\_F1} = 64.45\%$, while $TCS_{BB\_F1} = 10.63\%$. $TCS_{DW\_F1} = 9.81\%$, while $TCS_{LI\_F1} = 15.11\%$. Finally, the TCS of high forests (growing stock volume

GSV_{F2} = 196.39 $m^3 \cdot ha^{-1}$) was TCS_{F2} = 79.92 t $C \cdot ha^{-1}$. Of this, TCS_{AB_F2} = 64.24%, while TCS_{BB_F2} = 14.52%. TCS_{DW_F2} = 14.90%, while TCS_{LI_F2} = 6.34% (Figure 2).

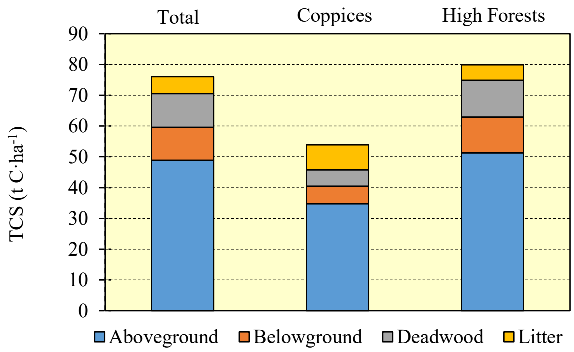

Figure 2. TCS at the starting year of the simulation (2016).

2.4.2 S_1 and S_3 Scenario assessment

Forests should be managed to deliver an optimal mix of social, environmental (including biodiversity conservation) and economic services in a sustainable way. The management options may lead to different outcomes, so that complex trade-offs may emerge (EASAC, 2017). At this purpose, forest management should consider the "multifunctionality" of the forests to balance their ecological, economic, and social functions by taking into account, at the same time, society's needs. The "multifunctionality" is thus a key aspect in forest management (EASAC, 2017) and it is linked to the concept of "sustainability", defined as *"the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems"* (EASAC, 2017). Considering all these elements, the main purpose of the S_1 Scenario was to calculate – by using a simplified method – the TCS of the forests at the deadline year of the most recent FMP, by assuming to adopt a multifunctional forest management approach. This latter is required both at the regional and landscape level and, above all, at the level of the single forest stand, that represents the reference unit of any FMP.

As reported in the Technical Handbook "Modelli di gestione forestale per il Parco dell'Adamello" ("Models of forest management for Adamello Park") (Ducoli, 2012), the multifunctional forest management should be based on the so called "open management systems" characterized by different management alternatives, to avoid exclusive forms of management. In other words, the open management systems make it possible to manage forests for both production purposes, as well as for purposes linked to biodiversity and landscape conservation, changing the management according to specific needs. For the Valle Camonica District, the concepts of "multifunctional forest management" and "open management systems" are widely recognized in the Forest Sector Plan. Alongside the more traditional needs of production of woody biomass (for biomass-to-energy processes and/or building purposes) and protection from erosion and hazard phenomena in general, new management needs emerged in the recent years. They are mainly linked to: (1) enhancement of biodiversity, (2) protection of slopes and landscape, and (3) usability of the forests from the recreational point of view. Regarding the gross annual increment, for the S_1 Scenario, results showed that:

- for C1 (coniferous stands with production function): average gross annual increment GAI_{AVC1} = 4.47 ± 2.78 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; minimum gross annual increment GAI_{MINC1} = 0.03 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; maximum gross annual increment GAI_{MAXC1} = 25.30 $m^3 \cdot ha^{-1} \cdot yr^{-1}$;

- for C2 (coniferous, broadleaves – both coppices and high forests – and mixed forests stands with protection function): GAI_{AVC2} = 1.73 ± 1.53 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; GAI_{MINC2} = 0.02 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; GAI_{MAXC2} = 10.35 $m^3 \cdot ha^{-1} \cdot yr^{-1}$;

- for C3 (broadleaves and mixed forests stands with production function, stands with recreational function and damaged stands to be recovered): GAI_{AVC3} = 2.80 ± 2.39 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; GAI_{MINC3} = 0.01 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; GAI_{MAXC3} = 15.56 $m^3 \cdot ha^{-1} \cdot yr^{-1}$;

- for C4 (coppices stands with production function): GAI_{AVC4} = 2.02 ± 1.48 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; GAI_{MINC4} = 0.05 $m^3 \cdot ha^{-1} \cdot yr^{-1}$; GAI_{MAXC4} = 13.00 $m^3 \cdot ha^{-1} \cdot yr^{-1}$.

Regarding the carbon storage, results showed that, in 2029 (total growing stock volume GSV_F = 186.89 $m^3 \cdot ha^{-1}$) TCS_F = 78.50 t $C \cdot ha^{-1}$. Of this, TCS_{AB_F} = 64.39%, while TCS_{BB_F} = 14.11%. TCS_{DW_F} = 14.36%, while TCS_{LI_F} = 7.13%. Taking into account the management system, for coppices (growing stock volume GSV_{F1} = 98.32 $m^3 \cdot ha^{-1}$) TCS_{F1} = 56.27 t $C \cdot ha^{-1}$. Of this, TCS_{AB_F1} = 64.99%, while TCS_{BB_F1} = 10.72%. TCS_{DW_F1} = 9.89%, while TCS_{LI_F1} = 14.39%. Finally, for high forests (growing stock volume GSV_{F2} = 202.54 $m^3 \cdot ha^{-1}$) TCS_{F2} = 82.42 t $C \cdot ha^{-1}$. Of this, TCS_{AB_F2} = 64.32%, while TCS_{BB_F2} = 14.52%. TCS_{DW_F2} = 14.90%, while TCS_{LI_F2} = 6.26% (Figure 3).

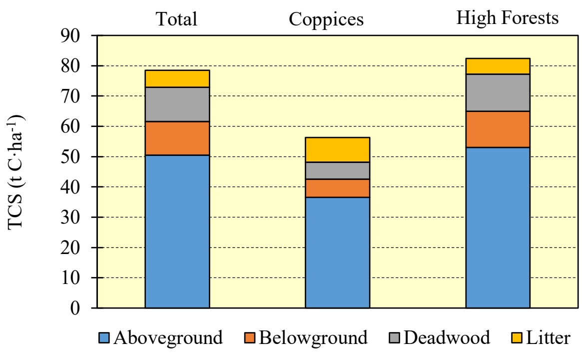

Figure 3. TCS for the S_1 Scenario (BAU_F, future business as usual, year 2029).

By adopting a multifunctional forest management approach, the TCS can increase by 2.48 t C·ha^{-1} (+3.26% of TCS in the year 2016).

However, the S_1 Scenario depends on some contingencies that cannot be preventively assessed: (1) extreme events, due to biotic and/or abiotic factors and (2) political constraints (up to now, despite the above-mentioned management should represent the ordinary situation, the financing of FMPs by Lombardy Region is uncertain for the future). The multifunctional management can promote a further increase of the annual increment and, therefore, a higher carbon sequestration. Moreover, the homeostatic capacity of forests can be enhanced and, as a general result, forests become more resistant to natural disturbances.

Considering all these elements, the possible strategies that can be adopted to improve the forest management of the District – not only in terms of carbon storage, but also to support the supply of the other ecosystem services – include: (1) an adequate financial support to the management practices defined in the FMPs and (2) the introduction of specific practices aimed to increase the medium-long term carbon sequestration.

Regarding the S_3 Scenario, under the assumption to convert: (1) *F. sylvatica* L. ($A_1 = 3.25 \cdot 10^2$ ha), (2) *Q. robur* L. and *Q. pubescens* Willd. ($A_2 = 3.87 \cdot 10^2$ ha), (3) *C. sativa* Mill. ($A_3 = 8.07 \cdot 10^2$ ha), and (4) *F. ornus* L. and *O. carpinifolia* Scop. ($A_4 = 1.76 \cdot 10^3$ ha), the TCS can be increased up to 79.49 t C·ha^{-1} (total area under conversion = $3.28 \cdot 10^3$ ha). Of this, TCS_{AB_F} = 64.56%, while TCS_{BB_F} = 14.09%. TCS_{DW_F} = 14.33%, while TCS_{LI_F} = 7.01% (Figure 4). The additional carbon – compared to the S_1 Scenario – that could be stored in the aboveground woody biomass and converted in CC for a local VCM was 0.78 t C·ha^{-1} (equal to 2.85 t CO_2·ha^{-1}).

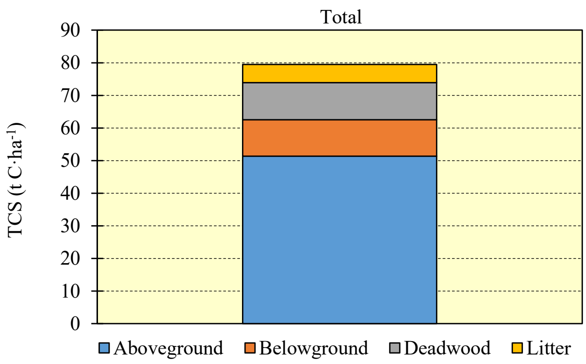

Figure 4. TCS for the S_3 Scenario (SST_F, future sustainable, year 2029).

As mentioned before, as a first approximation, in this first version of the model, it was hypothesized only the conversion of coppices to high forests since it is one of the main IFM practices promoted by the Mountain Community in the local Plan of Forest Sector.

In the second version of the model – that is currently under development – different practices will be defined for each stand. The assumption that coppices under conversion are characterized by the same gross annual increment reported for high forests stands is undoubtedly a simplification; in the active conversion of coppices to high forests, the growing stock temporarily decreases, and coppices do not immediately reach the same gross annual increment of the high forests. Therefore, through this method, an overestimation of the gross annual increment (and, therefore, of the wood biomass and carbon stocks) can occur. As mentioned before, not having any experimental data to work with, this simplification was considered acceptable within a short period of time and on the large scale considered by the study. In the second version of the model, wood biomass and carbon stocks of aged coppices under conversion will be calculated with more accuracy, by considering the temporary decrease of the gross annual increment. Moreover, wood biomass and carbon stocks were calculated until the deadline year of the most recent FMP (year 2029), without making any assumptions about the possible management practices after that year; this was done since different technical and natural conditions could lead to unreliable results. Because of this, the conversion of abandoned coppices to high forests through natural evolution was not considered since it will take place over a period higher than 12 years (period of time on which S_1 and S_3 Scenarios were based). Another important aspect that needs to be discussed is that, in all the Scenarios, the gross annual increment was assumed as constant within the same forest stand. This means that each stand is in equilibrium over time, excluding any dynamic effects. This undoubtedly limits the possibility of applying the model to a larger scale and directly reduces the accuracy of the results. Nevertheless, the above-mentioned simplification is generally applied also in any other FMPs in Italy. In the second version of the model the gross annual increment will be calculated as a function of the growing stock of the stand and species-specific growth parameters derived from the literature.

2.5 Conclusion

Estimating the TCS of forests is essential to support climate change mitigation. The adoption of a sustainable and multifunctional forest management approach is a key element to quantify the demand and the supply of different ecosystem services and to support the decision-making processes. This is important especially for mountainous areas, whose economy is heavily based on the use of local forestry resources. In these areas, the establishment of local VCMs could be an interesting solution to promote the transition into low-carbon emission economies, supporting the integration among natural resources, human society, and industrial processes.

This study presented a simplified model specifically developed to estimate, for the first time, the TCS of Valle Camonica District, by using site-specific primary data collected in 45 FMPs at the stand level. The model can be applied in any other forest area where similar input data are available. Even if the version described in this paper was undoubtedly simplified and the methodology is currently under improvement, the preliminary information reported by this study can already be used to update the data collected in the FMPs. The carbon storage was calculated not only in the aboveground wood biomass, but also for the belowground biomass, deadwood, and litter, generally not taken into account in the FMPs, but having a key role in defining the forests carbon stocks. The S_1 Scenario was introduced to calculate, as a first approximation, how much additional carbon could be stored by assuming to carry out a multifunctional forest management approach based on the continuation of current forest management over time. Finally, the conversion of coppices to high forests was investigated, being one of the main IFM system promoted by the Mountain Community in the local Plan of Forest Sector. This practice could promote the storage of additional carbon that, once converted into certified credits by a third part, can promote a local VCM and the transition into a low-carbon emission economy.

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Chapter 3 – Assessment of forest wood and carbon stock at the stand level: a modelling approach

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Abstract: To support local forestry authorities in forest management it is crucial to develop models able to provide information, on one hand, on the mass of wood and carbon (C) that forest can stock and, on the other hand, on the mass of residues that can be collected for energy generation. At this purpose, the first version of the empirical model WOody biomass and Carbon ASsessment (WOCAS v1) was improved into a second version (WOCAS v2). WOCAS v2 calculates – by using Forest Management Plans (FMP) data – the mass of wood ($t \cdot yr^{-1}$ of dry matter, DM) and carbon ($t \cdot yr^{-1}$ C) at the stand level, from the year in which FMPs entry into force up to a predefined reference year. At the same time, the model quantifies the mass of logging residues (branches and tops; $t \cdot yr^{-1}$ DM) that could have been collected, the potentially generated energy ($GJ \cdot yr^{-1}$) and the avoided CO_2 emissions ($t \cdot yr^{-1}$ CO_2) for the final combustion process, by assuming that residues substitute non-renewable energy sources. It this work it is presented the methodology implemented into WOCAS v2 to quantify the mass of wood ($t \cdot yr^{-1}$ DM) and C ($t \cdot yr^{-1}$ C), under the assumption that logging residues are left inside the stands. The mass of wood and C was calculated for aboveground wood biomass (AWB), belowground wood biomass (BWB) and dead organic matter (i.e., deadwood and litter; DOM) by applying an approach consistent with the 2006 IPCC Guidelines. The model was tested for the first time on 2019 public forest stands ($3.7 \cdot 10^4$ ha) of Valle Camonica District (Italy) for the period 1984-2016. For the whole analyzed period, the total harvested merchantable stem mass, calculated as the sum of the annual harvested mass in each stand, was $1.25 \cdot 10^5$ t DM and the corresponding total C mass was 6.25 $\cdot 10^4$ t C. In the year 2016, the annual living wood biomass (AWB + BWB) was $5.12 \cdot 10^6$ t DM, whereas DOM was $6.21 \cdot 10^5$ t DM. The average C yield for the whole analyzed period (1984-2016) was 66.04 $t \cdot ha^{-1}$ C (72.0% in AWB; 15.8% in BWB and 12.2% in DOM). Even if some methodological aspects needed to be improved and validation at the stand level was possible only for the gross annual increment, the information provided by this study can already be used to update FMPs data and to support sustainable forest management at the local scale.

Keywords: carbon stock, climate change mitigation, empirical models, forest stand, Richards function, wood biomass.

List of the parameters in the Text

Definition	Symbol	Unit
Wood basic density	k_1	$t \cdot m^{-3}$ of dry matter, DM
Maximum value of the merchantable stem mass at the beginning of the year n	k_2	$t \cdot ha^{-1} \cdot yr^{-1}$ DM
Growth parameter which allows to vary the time in which the merchantable stem mass at the beginning of the year n is equal to $k_2/2$	k_3	-
Relative growth rate	k_4	yr^{-1}
Shape parameter of the Richards function	k_5	-
Increment of the stand at the age of 1 year	k_6	$t \cdot ha^{-1} \cdot yr^{-1}$ DM
Biomass expansion factor	k_7	-
Parameter of the non-linear regression function for k_7 calculation	k_8	-
Parameter of the non-linear regression function for k_7 calculation	k_9	$t \cdot ha^{-1}$ DM
Root-to-shoot ratio	k_{10}	-
Deadwood biomass expansion factor	k_{11}	-

Fraction of aboveground wood biomass transferred to dead organic matter after disturbances	k_{12}	-
Dead organic matter decomposition rate	k_{13}	yr^{-1}
Carbon fraction of aboveground wood biomass DM	k_{14}	-
Carbon fraction of belowground wood biomass DM	k_{15}	-
Carbon fraction of dead organic matter DM	k_{16}	-

3.1 Introduction

Forests remove carbon (C) from the atmosphere through photosynthesis and accumulate it in both living aboveground and belowground biomass. A fraction of this C is transferred to deadwood, litter, and soil due to mortality and logging residues (branches and tops) that remain inside the forest after stem collection (IPCC, 2006; Morison et al., 2012; Seidl et al., 2014; Kurz et al., 2016).

At the same time, mortality, wood collection and the decomposition processes can cause the re-emission of the sequestered C directly into the atmosphere.

Mortality is due to both self-thinning and natural disturbances. Self-thinning is caused by senescence, competition for light, water and nutrient, and normal incident of pests, diseases, and weather phenomena (IPCC, 2006), whereas natural disturbances are caused by wildfires, windstorms, pest and insect's outbreaks, or other events that cause changes in forest structure and composition (Monserud, 1976; Vanclay, 1994).

Several models currently exist to estimate forest C stock; they differ according to the scale of application, the required input data, and the provided output results. Models can be classified as: (i) mechanistic or (ii) empirical.

Mechanistic models calculate the growth of the forest by considering the interaction among all the physiological processes on which the growth itself is based, i.e., photosynthesis, respiration, and allocation of photosynthates to roots, stems, and leaves. Each process is, in turn, described by considering ecological and environmental parameters such as light, temperature, soil nutrient and water content (Vanclay, 1994; Landsberg, 2003; Twery and Weiskittel, 2013). These models generally require extensive parameterization, complex input data and information that often are not made available from national/regional forest inventory. Moreover, the output results are not always of interest to forestry authorities and forest managers (Twery and Weiskittel, 2013).

On the contrary, empirical models describe the development of a forest by using regression equations that are parameterized from extensive datasets, without considering the processes that control forest growth and C stock from a physiological point of view (Vanclay, 1994; Twery and Weiskittel, 2013). According to the basic unit of modelling, the empirical models are classified into three categories: (i) single-tree; (ii) size class and (iii) whole-stand models (Vanclay, 1994; Twery and Weiskittel, 2013).

In the single-tree models, the single tree is the basic unit of modelling. These models require, as input, data about: (i) dimension of each tree (and, in some cases, distance among trees), (ii) tree height and (iv) crown characteristics, and provide, as output results, very detailed information about the growth of different tree compartments and their characteristics (Vancaly, 1994). Examples of single-tree models are TASS (Mitchell, 1975), PROGNAUS (Monserud et al., 1997), SILVA (Pretzsch et al., 2002) and FVS (Crookston and Dixon, 2005).

Size class models provide information regarding the structure of the stand, mainly by producing a histogram that represents the distribution of the stem diameters. This approach represents a compromise between whole stand models and single-tree models. When the class size is infinitely large and only one diameter class exists, the model is considered as a whole-stand model; on the contrary, when several diameter classes exist, the model is considered as a single-tree model (Vanclay, 1994; Twery and Weiskittel, 2013). Examples of size-class models are FIBER (Solomon et al., 1995) and CAFOGROM (Alder, 1995).

In whole-stand models, the basic unit of modelling is the stand. Total stand's volume, basal area, or density (number of trees per unit of area) are used to predict stand's growth over time (Vanclay, 1994; Twery and Weiskittel, 2013). Some widely used whole-stand models are DFSIM (Curtis et al., 1981), TADAM (García, 2005) and GNY (MacPhee and McGrath, 2006).

Empirical models are widely adopted in forest management (Twery and Weiskittel, 2013) since they are suitable to evaluate the impact of different silvicultural treatments on forest C stock (Böttcher et al., 2008, Verkerk et al., 2011). Nevertheless, since these models do not consider the effect of climate change and variation of soil productivity due to nitrogen deposition and increased atmospheric CO_2 concentration (Pretzsch et al., 2008), future projections should be limited to a short period of time in which forest growth and C stock is mainly affected by forest structure and silvicultural treatments (Pilli et al., 2014).

Empirical models are used at both continental (Böttcher et al., 2012), national (Federici et al., 2008; Pilli et al., 2013; Kim et al., 2016), regional (Anfodillo et al., 2006) or local scale.

This latter scale of analysis is particularly important for Italy, where public forests are managed through Forest Management Plans (FMP). Each FMP is generally approved by the Mountain Community, defined as a local authority that joins Alpine and pre-Alpine municipalities to improve social and economic conditions of marginalized mountainous areas of a particular territory (Dalla Valle et al., 2009). The basic management unit of each FMP is the forest stand, defined as an aggregation of trees over a specific area and sufficiently uniform in terms of species composition, structure and soil conditions to be distinguished from other aggregation of trees on adjoining areas.

For each stand, the FMP defines the silvicultural treatments to perform over a given period of time, while maintaining the productive, environmental, naturalistic, and social functions of the forest.
For each stand, the quantitative data that is generally made available by the FMP is the total merchantable stem volume of the trees. More specific data, such as the number of the trees, the average diameter, or the basal area, are not always made available. Under these conditions, using models that require single-tree level data is not always possible, and the only feasible solution consists in developing models in which the reference unit is the stand.
At this purpose, the first version of the empirical model WOody biomass and Carbon ASsessment (WOCAS v1) (Nonini and Fiala, 2019) was recently improved into a second version (WOCAS v2) by adopting a more accurate calculation methodology and improving the general structure of the model, to increase its reliability and flexibility.
WOCAS v2 calculates – by using FMPs data – the mass of wood ($t \cdot yr^{-1}$ of dry matter, DM) and carbon ($t \cdot yr^{-1}$ C) at the stand level in different ecosystem pools (Nonini et al., 2020), from the year in which the FMPs entry into force until a predefined reference year.
At the same time, WOCAS v2 quantifies the mass of logging residues (branches and tops; $t \cdot yr^{-1}$ DM) that could have been collected (potentially available logging residues), the corresponding potentially generated energy ($GJ \cdot yr^{-1}$) and the avoided CO_2 emissions ($t \cdot yr^{-1}$ CO_2) related to the final combustion process, under the hypothesis that wood substitutes non-renewable energy sources.
This work describes the methodology implemented into WOCAS v2 to quantify the mass of wood ($t \cdot yr^{-1}$ DM) and carbon ($t \cdot yr^{-1}$ C) in the forest stands.
Calculation of the potentially available logging residues is presented in another paper; therefore, in this work, it was assumed that logging residues were left inside the stands after silvicultural treatments. The methodology here described was tested for the first time on 2019 public forest stands (45 FMPs; 37000 ha) of Valle Camonica (Lombardy Region, Italy) and results are presented.

3.2 Materials and methods

Like WOCAS v1, also in WOCAS v2 the mass of wood and C is calculated through two spreadsheets: (i) parameters selection and (ii) carbon storage assessment. The first one contains a table in which the user defines different classification criteria, through the combination of the following sub-criteria (SC):

- SC_1 – forest structure;
- SC_2 – forest function;
- SC_3 – forest typology and variants.

A sub-code is assigned to each SC and the combination of these sub-codes generates a unique code (classification criteria code), by which proper calculation parameters are selected and uploaded into the second spreadsheet "carbon storage assessment". In it, the mass of wood and C is computed for each stand ("j") and for each year ("n") through a "gain-loss" approach consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) in (Figure 1):

- aboveground wood biomass (AWB);
- belowground wood biomass (BWB);
- dead organic matter (DOM).

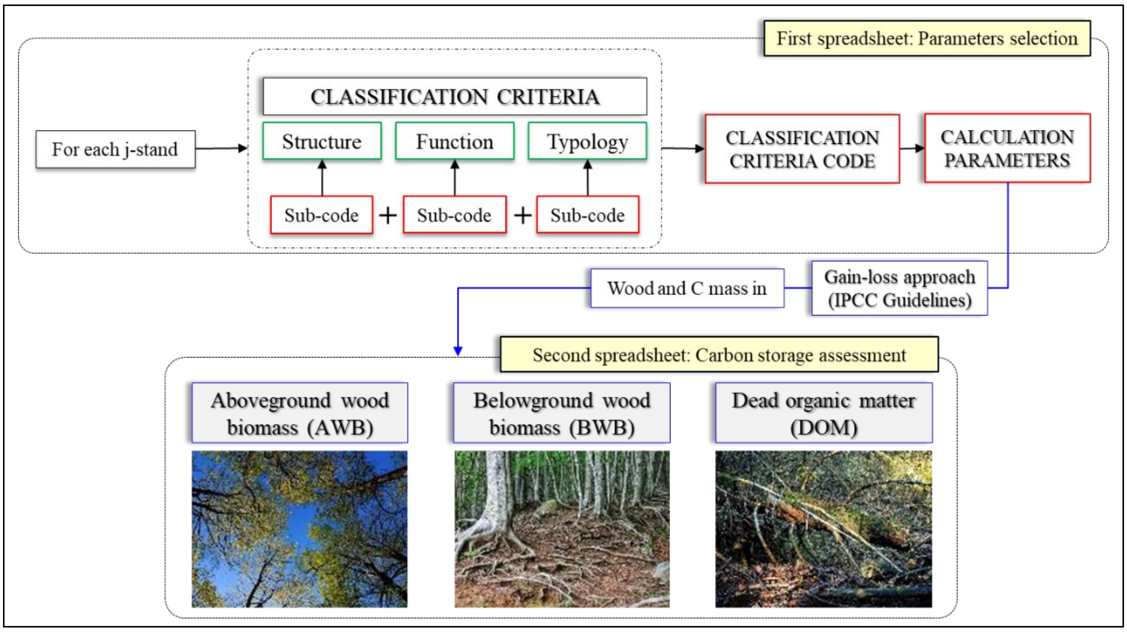

Figure 1. Logical framework implemented into WOCAS v2 to define the calculation parameters used to quantify the mass of wood and C in the pools (Source of pictures: www.pixabay.com)

The definition of the above-mentioned pools is given in Table 1.

Table 1. Definition of the pools taken into account by WOCAS v2 (Source: IPCC, 2006; Federici et al., 2008).

N.	Name	Definition
1	Aboveground wood Biomass (AWB)	Over-bark living wood biomass above the soil surface related to stems and branches of all dimensions. Foliage is excluded.
2	Belowground wood Biomass (BWB)	Living wood biomass of coarse live roots (diameter ≥ 2 mm). Fine roots (diameter < 2 mm) are included in the soil organic matter or litter, since they cannot be empirically distinguished from them.
3	Dead organic Matter (DOM)	Deadwood: all non-living wood biomass not contained in the litter, both standing and lying on the soil surface, with diameter ≥ 10 cm.
		Litter: all non-living wood biomass with diameter < 10 cm. It includes wood in different stages of decomposition above the mineral or organic soil, and fine roots.

In the “carbon storage assessment” spreadsheet, the following input data are required for each j-stand:

- starting ($YR_{S(j)}$) and deadline ($YR_{D(j)}$) year of the FMP;
- forest structure;
- forest function;
- forest typology and variants;
- area ($A_{(j)}$; ha);
- merchantable stem volume ($MV_{n(j)}$; $m^3 \cdot yr^{-1}$) at $YR_{S(j)}$;
- gross annual increment of merchantable stem volume ($GAI^*_{n(j)}$; $m^3 \cdot yr^{-1}$) at $YR_{S(j)}$;
- harvested merchantable stem volume over time ($MV_{Hn(j)}$; $m^3 \cdot yr^{-1}$).

$MV_{n(j)}$ is the volume of the stem over-bark excluding all branches and foliage. Before the calculations, all the volume values are converted into mass values through the parameter k_1 (wood basic density, i.e., ratio between wood DM and wood fresh volume; $t \cdot m^{-3}$ DM).

Figure 2 shows the general approach implemented into WOCAS v2 for each j-stand for the quantification of the mass of wood ($t \cdot yr^{-1}$ DM) and C ($t \cdot yr^{-1}$ C) within the above-mentioned pools.

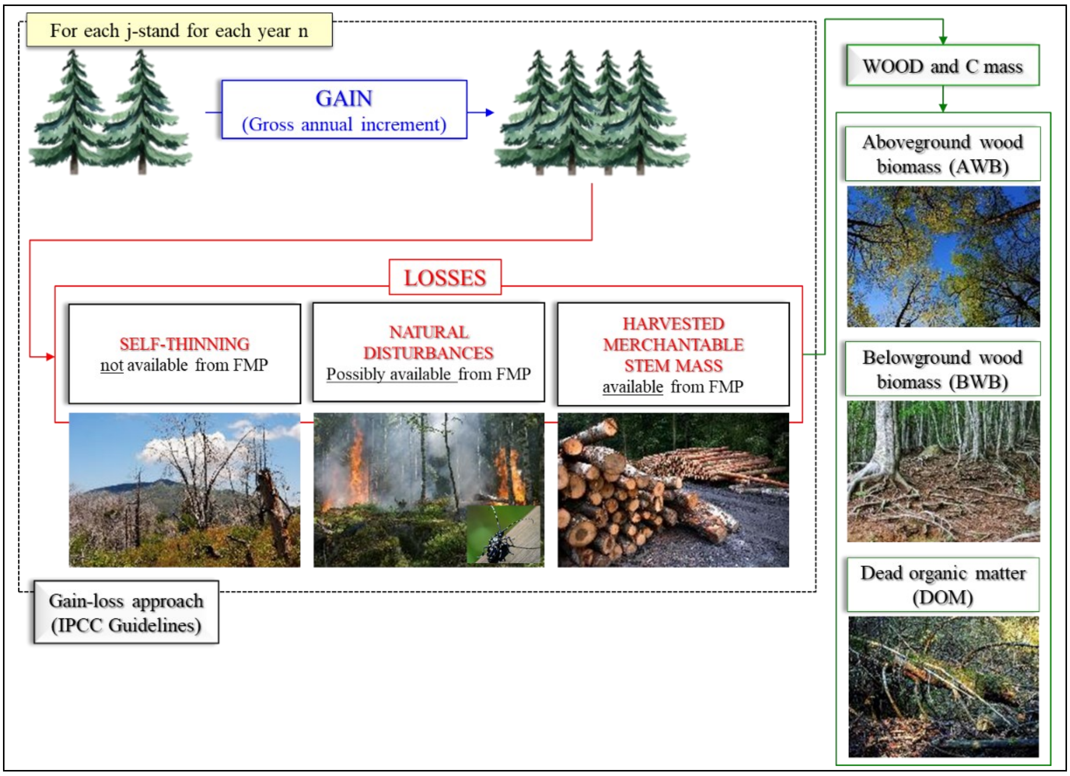

Figure 2. Schematization of the general approach used in WOCAS v2 to compute the mass of wood and C in the pools (Source of pictures www.pixabay.com).

The following paragraphs describe in detail the methodology that is implemented into the model.

3.2.1 Gross annual increment

FMPs provide, for each stand, data on the gross annual increment (GAI; $m^3 \cdot yr^{-1}$) that, by definition, includes the increment of living trees plus the increment of trees which will die within the same period of time, due to silvicultural treatments or mortality (self-thinning and natural disturbances). This GAI is provided for the starting year of the Plan and is assumed as constant over time. This is a quite strong assumption, since the increment varies year by year according to stand's age, volume, environmental conditions, and silvicultural treatments. When developing a forest model of wood and C dynamic, the calculation of the annual GAI of the forest is an essential step.

In forest modelling, the increment of the stands was always related to the age for the definition of the proper rotation period. Age could be used to calculate the increment for a single tree, but not for the whole stand, where self-thinning and natural regeneration generally lead to the presence of trees of different ages (Tulipano, 2005).

Moreover, several studies showed that the growth of trees and stands can be computed without explicitly considering the age (Birch, 1999; Thrower, 2003; Chrimes, 2004). An analysis performed by Lähde et al. (1994) for different forest structures and compositions showed a higher correlation between annual increment and volume rather than between annual increment and age. Many empirical and theoretical functions can be used to compute GAI of the stands.

In WOCAS v2, GAI is calculated by using the theoretical function of Richards (Richards, 1959; Pienaar and Turnbull, 1973) since:

- it describes the process of growth from a biological point of view;
- GAI is computed only according to the merchantable stem mass (MM; $t \cdot yr^{-1}$ DM) of the stand, without considering the age; as a result, GAI can be calculated for both even-aged and uneven-aged stands.

The Richards function can be expressed as:

$$MM^{*}_{n(j)} = k_{2(j)} \cdot \left[1 - e^{(k_{3(j)} - k_{4(j)} \cdot t)}\right]^{-1/k_{5(j)}} \quad \text{(Eq. 1)}$$

where:

$MM^{*}_{n(j)}$: merchantable stem mass at the beginning of the year n per unit of area ($t \cdot ha^{-1} \cdot yr^{-1}$ DM);

$k_{2(j)}$: maximum value of $MM^{*}_{n(j)}$, i.e., carrying capacity ($t \cdot ha^{-1} \cdot yr^{-1}$ DM; $k_{2(j)} > 0$);

e: Euler's number (constant equal to 2.718);

$k_{3(j)}$: growth parameter which allows the time at which $MM^{*}_{n(j)} = k_{2(j)}/2$ to be varied (dimensionless);

$k_{4(j)}$: relative growth rate, i.e., rate of accumulation of new DM per unit of existing DM (yr^{-1}; $k_{4(j)} > 0$);

t: time (years);

$k_{5(j)}$: shape parameter which allows the curve inflexion point to be at any point between the minimum and the maximum value of the merchantable stem mass (dimensionless; $-1 \leq k_{5(j)} \leq +\infty$; $k_{5(j)} \neq 0$);

The Richards function is expressed as a non-linear regression curve with a sigmoid trend (Figure 3), in which the rate of growth increases as size increases from low values, reaches a maximum at the point of inflexion, and then decreases towards zero at an upper asymptote. This function is a generalization of most used growth functions, such as the exponential (when $k_{2(j)} \to +\infty$ and $k_{5(j)} > 0$), the logistic (when $k_{5(j)} > 1$), the Bertalanffy (when $k_{5(j)} = 3$) and the Gompertz ($k_{5(j)} \to \pm\infty$).

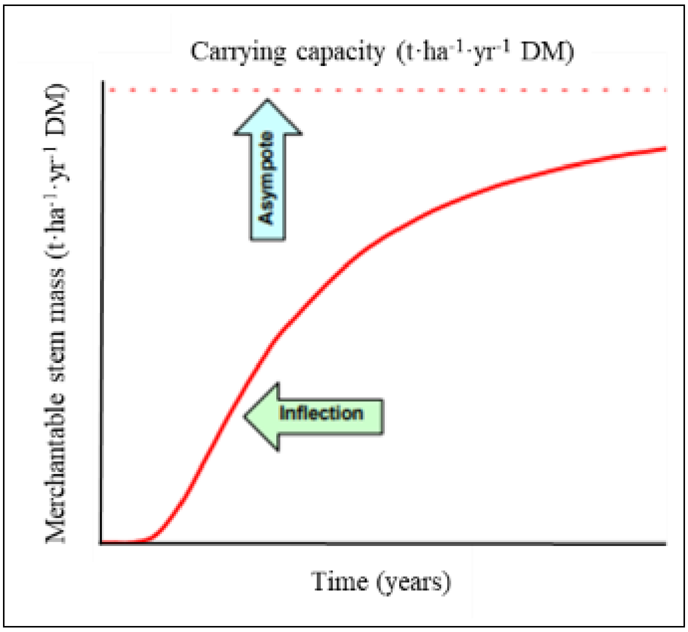

Figure 3. Example of the trend of the Richards function. There are two key features: (i) carrying capacity (or asymptote), that represents the maximum limit towards which the merchantable stem mass tends as time passes, and (ii) inflection point, that is the point in which the growth reaches the maximum (Source: modified from Alder et al., 2003).

For each j-stand and for each year n, $GAI_{n(j)}$ ($t \cdot yr^{-1}$ DM) is calculated through the first derivative of the merchantable stem mass with respect to time (Federici et al., 2008):

$$GAI_{n(j)} = \left[\frac{k_{4(j)}}{k_{5(j)}} \cdot MM^{*}_{n(j)} \cdot \left[1 - \left(\frac{MM^{*}_{n(j)}}{k_{2(j)}}\right)^{k_{5(j)}}\right] + k_{6(j)}\right] \cdot A_{(j)} \qquad \text{(Eq. 2)}$$

where:

$A_{n(j)}$: area of the stand (ha);

$k_{6(j)}$: increment of the stand at the age of 1 year; this parameter does not derive from the calculation of the first derivative, but it is necessary to define the starting point of the function ($t \cdot ha^{-1} \cdot yr^{-1}$ DM; $k_{6(j)} > 0$);

The parameters $k_{2(j)}$, $k_{4(j)}$, $k_{5(j)}$ and $k_{6(j)}$ are defined for each j-stand at the beginning of the simulation in the "parameters selection" spreadsheet and are assumed as constant over time.

As an example, Figure 4 shows the gross annual increment for *Picea abies* L. and *Larix decidua* Mill. calculated by applying the Eq. 2 by using specific calibrated parameters valid for the Lombardy Region (Vitullo and Federici, 2018). It is clearly shown that, in the initial stages of growth, when the merchantable stem mass is lower than the carrying capacity, $GAI_{n(j)}$ increases year-by-year; after the inflection point, $GAI_{n(j)}$ decreases year by year; finally, when the merchantable stem mass is equal to the carrying capacity $GAI_{n(j)} = 0$ $t \cdot ha^{-1} \cdot yr^{-1}$ DM.

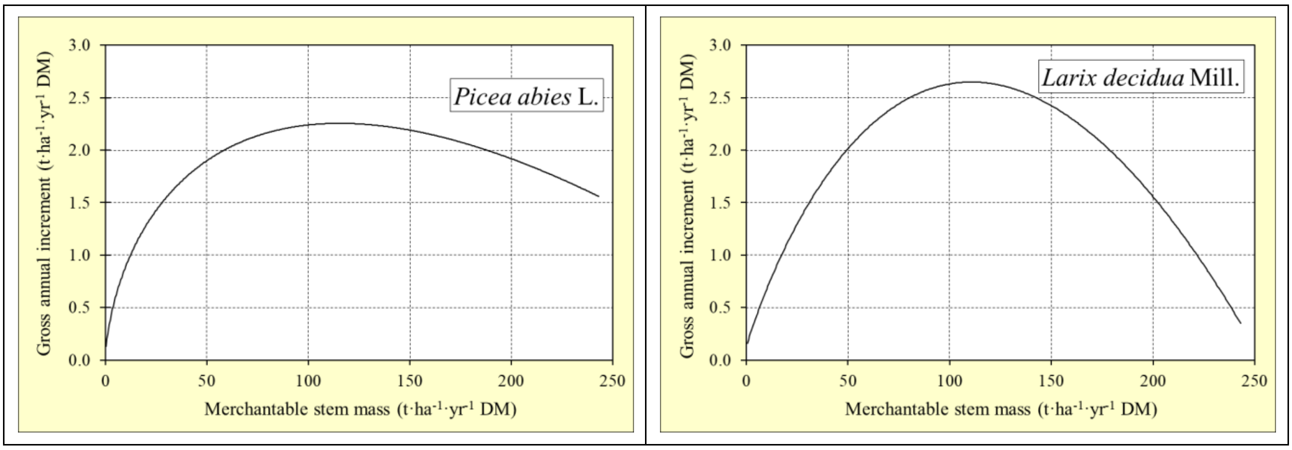

Figure 4. Gross annual increment calculated by applying the Eq. 2 with specific calibrated parameters valid for the Lombardy Region for (i) *Picea abies* L. (left) and (ii) *Larix decidua* Mill. (right).

Once $GAI_{n(j)}$ is computed, WOCAS v2 calculates the aboveground and belowground wood biomass and the dead organic matter, by taking into account the net annual increment and the harvested merchantable stem mass, as described in detail in the following paragraphs. Finally, the mass of C in each pool is quantified.

3.2.2 Net annual increment

The net annual increment ($NAI_{n(j)}$; $t \cdot yr^{-1}$ DM) is calculated by subtracting from $GAI_{n(j)}$ losses of merchantable stem mass due to both self-thinning ($MM_{Sn(j)}$; $t \cdot yr^{-1}$ DM) and natural disturbances ($MM_{Dn(j)}$; $t \cdot yr^{-1}$ DM) (Kuusela, 1994; Schuck et al., 2002):

$$\mathrm{NAI_{n(j)} = GAI_{n(j)} - MM_{Sn(j)} - MM_{Dn(j)}} \qquad \text{(Eq. 3)}$$

Self-thinning occurs each year; in natural stands without periodic wood cuts, it can represent 30-50% of $GAI_{n(j)}$ whereas, in regularly managed stands, it can be negligible since cuts remove wood that otherwise would be lost and transferred to the DOM (IPCC, 2006). According to Harmon et al. (2001), losses due to self-thinning is at maximum equal to 1% of the merchantable stem mass ($MM_{n(j)}$; $t \cdot yr^{-1}$ DM).

In WOCAS v2 the user must choose whether to express $MM_{Sn(j)}$ as a fraction of $MM_{n(j)}$ (0 – 1 %), or as a fraction of $GAI_{n(j)}$ (0 – 50 %); moreover, the user can use the average value or any other value between the minimum and maximum one.

For natural disturbances, the user must define: (i) targeted volume ($m^3 \cdot yr^{-1}$), (ii) type of disturbance (wildfire, windstorm, insect outbreak, or other) and (iii) the year in which the disturbance occurs. To compute $MM_{Dn(j)}$ ($t \cdot yr^{-1}$ DM) the targeted volume provided by the user is converted by the model into targeted mass through the parameter k_1.

3.2.3 Harvested merchantable stem mass

For each j-stand and for each year n in which wood cuts occurred, the harvested merchantable stem mass ($MM_{Hn(j)}$; $t \cdot yr^{-1}$ DM) is computed as (IPCC, 2006):

$$\mathrm{MM_{Hn(j)} = MV_{Hn(j)} \cdot k_1} \qquad \text{(Eq. 4)}$$

At the same time, WOCAS v2 calculates the mass of logging residues that could have been produced (potentially produced logging residues) after wood cuts ($RP_{n(j)}$; $t \cdot yr^{-1}$ DM) as (IPCC, 2006):

$$\mathrm{RP_{n(j)} = (MM_{Hn(j)} \cdot k_7) - MM_{Hn(j)}} \qquad \text{(Eq. 5)}$$

The parameter k_7 is the biomass expansion factor, i.e., total aboveground wood volume on merchantable stem volume. Under the assumption that k_7 is constant among wood components, i.e., stem and branches, k_7 can also be defined as the total aboveground wood biomass DM on merchantable stem mass DM.

To increase the flexibility of WOCAS v2 and its applicability for larger scales and for forest stands of any conditions, $RP_{n(j)}$ can be calculated by using, alternatively: (i) constant values of k_7 defined for each classification criteria code or (ii) variable values defined for each stand each year starting from the harvested merchantable stem mass per unit of area (Teobaldelli et al., 2009):

$$k_{7n(j)} = k_{8(j)} + k_{9(j)}/MM^{*}_{Hn(j)} \quad \text{(Eq. 6)}$$

where:

$MM^{*}_{Hn(j)}$ = harvested merchantable stem mass at the year n per unit of area ($t \cdot ha^{-1} \cdot yr^{-1}$ DM);

k_8, k_9 = parameters of the non-linear regression function, defined for each classification criteria code (k_8: dimensionless; k_9: $t \cdot ha^{-1}$ DM).

3.2.4 Aboveground and belowground wood biomass

The merchantable stem mass at the end of the year n ($MM'_{n(j)}$; $t \cdot yr^{-1}$ DM) is calculated starting from the merchantable stem mass at the beginning of the year n ($MM_{n(j)}$; $t \cdot yr^{-1}$ DM), adding $NAI_{n(j)}$ ($t \cdot yr^{-1}$ DM) and subtracting $MM_{Hn(j)}$ ($t \cdot yr^{-1}$ DM):

$$MM'_{n(j)} = MM_{n(j)} + NAI_{n(j)} - MM_{Hn(j)} \quad \text{(Eq. 7)}$$

The aboveground and belowground wood biomass DM at the end of the year n ($AWB_{n(j)}$, $BWB_{n(j)}$, respectively; $t \cdot yr^{-1}$ DM) are computed as:

$$AWB_{n(j)} = MM'_{n(j)} \cdot k_7 \quad \text{(Eq. 8)}$$

$$BWB_{n(j)} = MM'_{n(j)} \cdot k_{10} \quad \text{(Eq. 9)}$$

where:

k_{10}: root-to-shoot ratio, i.e., belowground root mass DM on merchantable stem mass DM.

Also in this case, $AWB_{n(j)}$ can be calculated by using alternatively: (i) constant values of k_7 defined for each classification criteria code or (ii) variable values defined for each stand each year (Teobaldelli et al., 2009), computed as a function of $MM'_{n(j)}$. For each j-stand, the total living biomass is quantified:

$$TLB_{n(j)} = AWB_{n(j)} + BWB_{n(j)} \quad \text{(Eq. 10)}$$

3.2.5 Dead organic matter

The mass of wood in the DOM at the end of the year n ($DOM_{n(j)}$; $t \cdot yr^{-1}$ DM) is calculated starting from the DOM at the beginning of the year n ($DOM'_{n(j)}$; $t \cdot yr^{-1}$ DM), adding the DOM inputs ($DOM_{INn(j)}$; $t \cdot yr^{-1}$ DM) and subtracting the DOM output ($DOM_{OUTn(j)}$; $t \cdot yr^{-1}$ DM) (IPCC, 2006):

$$\mathrm{DOM_{n(j)} = DOM'_{n(j)} + DOM_{INn(j)} - DOM_{OUTn(j)}} \quad \text{(Eq. 11)}$$

Only for the starting year of the simulation, $DOM'_{n(j)}$ is computed as:

$$\mathrm{DOM'_{n(j)} = MM_{n(j)} \cdot k_7 \cdot k_{11}} \quad \text{(Eq. 12)}$$

k_{11} is the deadwood biomass expansion factor (deadwood DM on aboveground wood biomass DM).

$DOM_{INn(j)}$ is calculated as:

$$\mathrm{DOM_{INn(j)} = (MM_{Sn(j)} \cdot k_7) + (MM_{Sn(j)} \cdot k_{10}) + (MM_{Dn(j)} \cdot k_7 \cdot k_{12}) + (MM_{Dn(j)} \cdot k_{10}) + RP_{n(j)} + (MM_{Hn(j)} \cdot k_{10})} \quad \text{(Eq. 13)}$$

where:

$MM_{Sn(j)} \cdot k_7$: aboveground wood biomass transferred to DOM due to self-thinning;

$MM_{Sn(j)} \cdot k_{10}$: belowground wood biomass transferred to DOM due to self-thinning;

$MM_{Dn(j)} \cdot k_7 \cdot k_{12}$: aboveground wood biomass transferred to DOM due to natural disturbances; k_{12} (-) is the fraction of aboveground wood biomass that is transferred to DOM according to the type of disturbances. As default, in the case of wildfire, a value of $k_{12} = 0.5$ is adopted by WOCAS v2 (Piedmont Region, 2010), under the hypothesis that 50% of the aboveground wood biomass is transferred to the DOM and the other fraction is lost through the atmosphere. For all the other types of disturbances, as default, a value of $k_{12} = 1$ is used, i.e., 100% of the aboveground wood biomass is transferred to the DOM.

$MM_{Dn(j)} \cdot k_{10}$: belowground wood biomass transferred to DOM due to natural disturbances;

$RP_{n(j)}$: potentially produced logging residues from wood cuts;

$MM_{Hn(j)} \cdot k_{10}$: belowground wood biomass transferred to DOM due to wood cuts.

$DOM_{OUTn(j)}$ ($t \cdot yr^{-1}$ DM) refers to the decomposition, and is computed as:

$$DOM_{OUTn(j)} = (DOM'_{n(j)} + DOM_{INn(j)}) \cdot k_{13} \quad \text{(Eq. 14)}$$

k_{13} is the DOM decomposition rate, i.e., fraction of DOM that annually decomposes (yr^{-1}).

Figure 5 shows the logical framework implemented into WOCAS v2 to compute the mass of wood in the DOM for each j-stand for each year n.

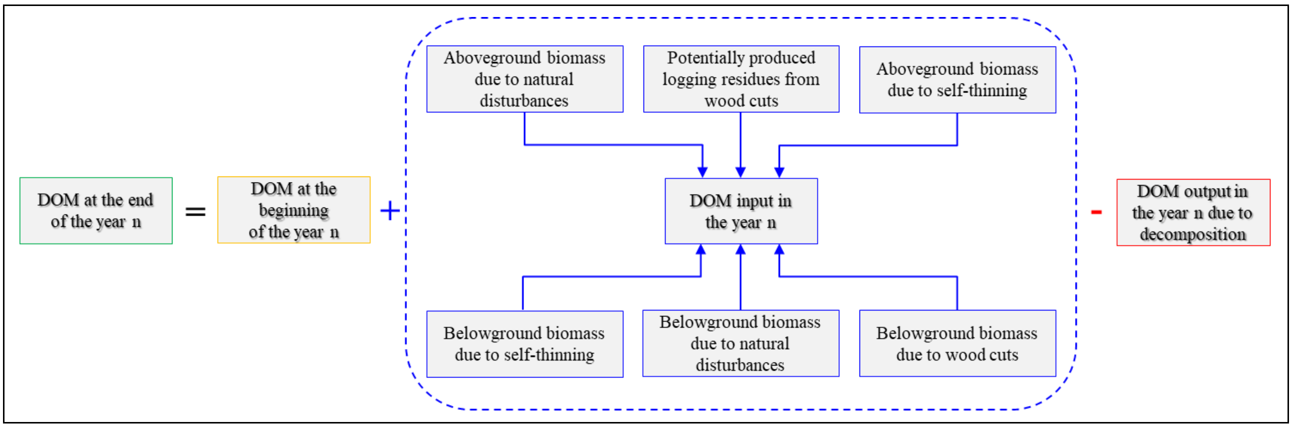

Figure 5. Logical framework for the quantification of the mass of wood in the DOM for each j-stand for each year n.

3.2.6 Carbon mass

For each j-stand and for the year n, the mass of C in: (i) ABW ($C_{AWBn(j)}$, $t \cdot yr^{-1}$), (ii) BWB ($C_{BWBn(j)}$, $t \cdot yr^{-1}$) and (iii) DOM ($C_{DOMn(j)}$, $t \cdot yr^{-1}$) is calculated as the product between the mass of wood in each pool and the corresponding carbon fraction, defined for each classification criteria code:

$$C_{AWBn(j)} = AWB_{n(j)} \cdot k_{14} \quad \text{(Eq. 15)}$$

$$C_{BWBn(j)} = BWB_{n(j)} \cdot k_{15} \quad \text{(Eq. 16)}$$

$$C_{DOMn(j)} = DOM_{n(j)} \cdot k_{16} \quad \text{(Eq. 17)}$$

where:

k_{14} is carbon fraction of aboveground wood biomass DM;

k_{15} is carbon fraction of belowground wood biomass DM;

k_{16} is carbon fraction of dead organic matter DM.

By summing up $C_{AWBn(j)}$, $C_{BWBn(j)}$ and $C_{DOMn(j)}$, the total carbon mass of each j-stand ($C_{TOTn(j)}$; $t \cdot yr^{-1}$ C) is computed:

$$C_{TOTn(j)} = C_{AWBn(j)} + C_{BWBn(j)} + C_{DOMn(j)} \quad \text{(Eq.18)}$$

3.3 Case Study

Valle Camonica has a total area equal to $A_T = 1.27 \cdot 10^5$ ha. Forests cover an area of $A_F = 6.5 \cdot 10^4$ ha, (52% of A_T). Public forests (managed through FMPs) reach $4.2 \cdot 10^4$ ha (64% of A_F), whereas private forests (not managed through FMPs) cover the remaining $2.3 \cdot 10^4$ ha.

According to a recent estimation of the Mountain Community carried out in the year 2016, the total merchantable stem volume is $6.2 \cdot 10^6$ m^3, approximately, and the total gross annual increment is $1.2 \cdot 10^5$ $m^3 \cdot yr^{-1}$, approximately.

For the study, data of 2019 forest stands (45 FMPs; total area: $3.67 \cdot 10^4$ ha) were extracted from the "Cadastral FMPs database" (CPA v2) made available by the Mountain Community. Data referred to the period between 1984 (starting year of the oldest FMP) and 2016 (more recent data made available by the CPA v2).

In the local FMPs, the merchantable stem volume of high forests is referred to the volume of the stem over bark, from stump (30 cm above the forest floor) up to a top diameter of 7 cm of all living trees with a diameter at breast height higher than 17.5 cm. Branches and foliage are always excluded. The merchantable volume of coniferous is calculated by using specific diameter-height relations defined for the Trentino-Alto-Adige Region, whereas the merchantable volume of broadleaves is estimated by using, as a reference, diameter-height relations defined for *Fagus Sylvatica* L. for the Lombardy Region. Merchantable volume of coppices is generally estimated by using standard values defined for each forest typology (Del Favero, 2002). The 2019 stands are characterized by 66 forest typologies, aggregated – according to the main species – into 12 forest categories (Table 2).

Table 2. Forest categories based on the main species: stands' number and area.

Forest category	Main species	Stands	
		(n.)	(ha)
1	*Picea abies* L.	1125 (55.7%)	19506.4 (53.1%)
2	*Larix decidua* Mill.	356 (17.6%)	8288.0 (22.6%)
3	*Alnus viridis* Chaix D.C., *Betula* L., *Corylus avellana* L.; *Sorbus aucuparia* L., other species with high physiognomic-structural disorders	185 (9.2%)	3617.4 (9.8%)
4	*Fraxinus ornus* L., *Ostria carpinifolia* Scop., *Quercus pubescens* Willd.	112 (5.5%)	1838.5 (5.0%)
5	*Castanea sativa* Mill.	63 (3.1%)	860.6 (2.3%)
6	*Picea abies* L. and *Fagus sylvatica* L.	45 (2.2%)	646.5 (1.8%)

7	*Fagus sylvatica* L.	41 (2.0%)	584.6 (1.6%)
8	*Quercus robur* L.	29 (1.4%)	459.2 (1.2%)
9	*Acer pseudoplatanus* L., *Tilia cordata* Mill., *Fraxinus ornus* L.	26 (1.3%)	414.4 (1.1%)
10	*Abies alba* Mill.	24 (1.2%)	340.5 (0.9%)
11	*Pinus sylvestris* L.	8 (0.4%)	111.3 (0.3%)
12	*Pinus montana* Mill; *Robinia pseudoacacia* L.	5 (0.2%)	74.4 (0.2%)
	Total	2019 (100%)	36741.8 (100%)

Table 3 shows management systems, forest functions, stand's number, and area.

Table 3. Management systems, functions, stands' number, and area.

Management system	**Function**	**Family**	**Stands**			
			Number	**Area**		
				Total	**min÷max**	**Average ± s.d (*)**
			(-)	**(ha)**	**(ha)**	**(ha)**
High forest	Production	Coniferous	1063 (52.6%)	17480.9 (47.6%)	1.4÷50.0	16.4±7.6
		Broadleaves	7 (0.3%)	97.6 (0.3%)	7.5÷25.3	13.9±6.3
		Mixed	96 (4.8%)	1615 (4.5%)	3.8÷45.0	16.8±8.5
	Protection	Coniferous	445 (22.0%)	10816.3 (29.4%)	2.2÷110.0	24.3±14.8
		Broadleaves	4 (0.2%)	44.2 (0.1%)	8.6÷14.0	11.1±2.2
		Mixed	20 (1.0%)	356.4 (1.0%)	2.0÷38.6	17.8±9.7
	Recreational	Coniferous	25 (1.2%)	641.3 (1.7%)	6.2÷49.8	25.7±11.2
	Other	Coniferous	7 (0.3%)	38.4 (0.1%)	1.3÷14.2	5.5±5.0
		Broadleaves	7 (0.3%)	117.4 (0.3%)	5.5÷35.7	16.8±10.0
Coppice	Production	Broadleaves	196 (9.7%)	3191.5 (8.7%)	1.3÷65.5	16.3±9.5
	Protection		73 (3.6%)	1328.9 (3.6%)	0.8÷96.0	18.2±16.4
	Recreational		5 (0.2%)	78.9 (0.2%)	2.4÷32.5	15.8±15.3
	Other		71 (3.5%)	934.9 (2.5%)	2.3÷34.8	13.2±7.2
Total	-	-	2019 (100%)	36741.8 (100%)	0.8÷110.0	18.2±10.9

(*) Standard deviation.

To compute $GAI_{n(j)}$ the values of k_2, k_4, k_5 and k_6 reported in the National Inventory Report (NIR) for the Land Use, Land Use Change and Forestry (LULUCF) sector of the Lombardy Region (Vitullo and Federici, 2018) were used. To calculate $NAI_{n(j)}$, since experimental data at the stand level were not available, $MM_{Sn(j)}$ was assumed equal to 10% $GAI_{n(j)}$ (Magnani and Raddi, 2014). $MM_{Dn(j)}$ was not considered since no data on the targeted merchantable stem volume were made available from the CPA v2. $AWB_{n(j)}$ and $BWB_{n(j)}$ were calculated by considering, respectively, the values of k_7 and k_{10} reported in Federici et al. (2008) for Italian forest species.

The mass of wood in the DOM at the starting year of the simulation was computed by assuming values of k_{11}= 0.25 and k_{11} = 0.15 for coniferous and broadleaves stands, respectively (Harmon et al., 2001); DOM decomposition was estimated by applying a value of k_{13} = 0.032 yr^{-1} and k_{13} = 0.080 yr^{-1} for coniferous and broadleaves stands, respectively (Harmon et al., 2001).

To quantify the mass of C in AWB, different values of k_{14} were adopted for each classification criteria code, according to the carbon content of the main species. If specific values were not available, general values equal to k_{14} = 0.508 for coniferous and k_{14} = 0.477 for broadleaves were considered

(Thomas and Martin, 2012). The mass of C in BWB and DOM was quantified by assuming that $k_{14} = k_{15} = k_{16}$.

3.4 Results and discussion

3.4.1 Gross annual increment and merchantable stem mass

At the stand level, comparison between the gross annual increments predicted through the Richards function ($GAI_{n(j)}$; $t \cdot ha^{-1} \cdot yr^{-1}$ DM) and the ones provided by FMPs ($GAI^{*}_{n(j)}$; $t \cdot ha^{-1} \cdot yr^{-1}$ DM) showed that the application of the Richards function caused, in some cases, an overestimation ($GAI_{n(j)} > GAI^{*}_{n(j)}$), whereas, in other cases, an underestimation ($GAI_{n(j)} < GAI^{*}_{n(j)}$). Figure 6 shows this comparison for *Larix decidua* Mill. for the year 2002.

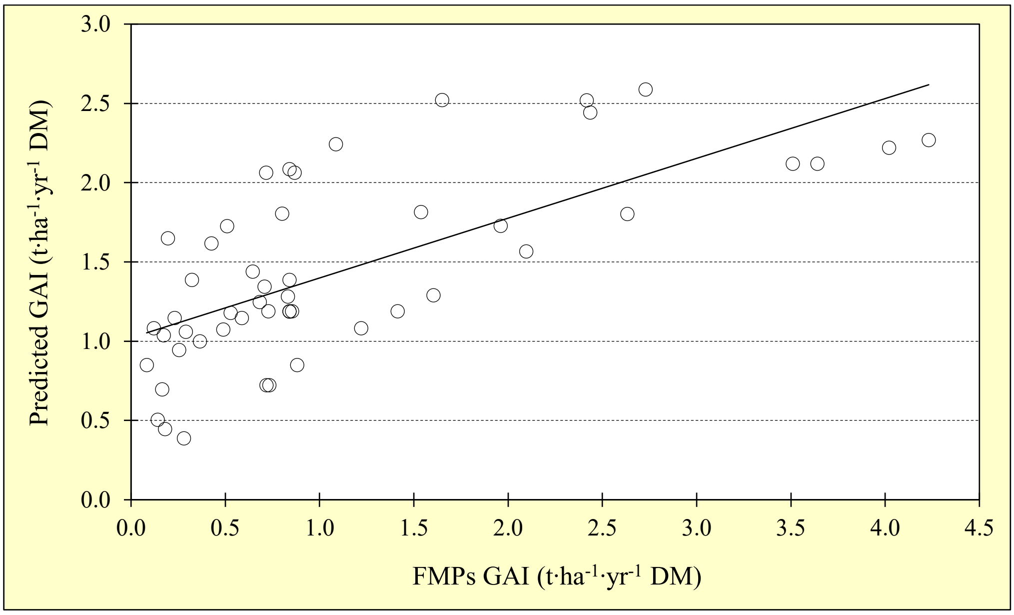

Figure 6. Comparison between GAI predicted through the Richards function and GAI provided by the FMPs for *Larix decidua* Mill. for the year 2002 (number of stands: 50)

The main statistical parameters are shown in Table 4.

Table 4. Comparison between the gross annual increments predicted through the Richards function and the ones provided by the FMPs for *Larix decidua* Mill. for the year 2002: main statistical parameters.

Type of GAI	Min	Max	Range of Variation	Weighted average	Weighted standard deviation	RMSE	r^2
	$t \cdot ha^{-1} \cdot yr^{-1}$ DM						-
Predicted (Richards function)	0.39	2.59	2.20	1.26	0.58	0.84	0.69
Provided (FMPs)	0.08	4.23	4.15	0.89	0.86		

Figure 7 shows the comparison between $GAI_{n(j)}$ ($t \cdot ha^{-1} \cdot yr^{-1}$ DM) and $GAI^{*}_{n(j)}$ ($t \cdot ha^{-1} \cdot yr^{-1}$ DM) for *Picea abies* L., which is the main species of the Case Study Area, for the year 2002.

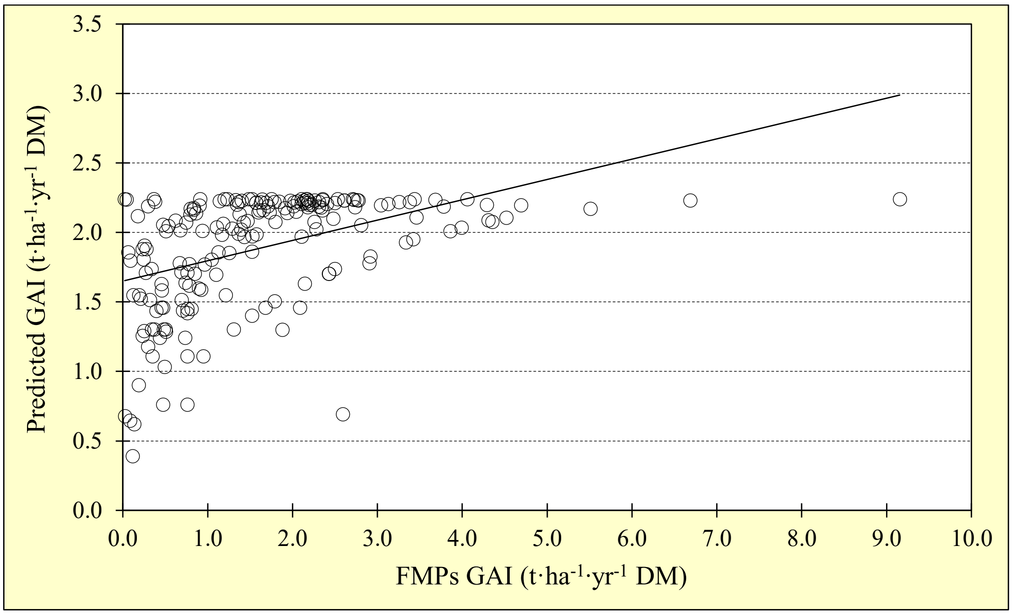

Figure 7. Comparison between GAI predicted through the Richards function and GAI provided by the FMPs for *Picea abies* L. for the year 2002 (number of stands: 188)

The main statistical parameters are shown in Table 5.

Table 5. Comparison between the gross annual increments predicted through the Richards function and the ones provided by the FMPs for *Picea abies* L. for the year 2002: main statistical parameters.

Type of GAI	**Min**	**Max**	**Range of Variation**	**Weighted average**	**Weighted standard deviation**	**RMSE**	**r^2**
	$t \cdot ha^{-1} \cdot yr^{-1}$ DM						-
Predicted (Richards function)	0.39	2.24	1.85	1.81	0.45	1.19	0.46
Provided (FMPs)	0.02	9.15	9.13	1.49	1.18		

In some cases, r^2 between GAI predicted through the Richards function and GAI provided by the FMPs was even lower that 0.46, and the main reasons were the following:

- $GAI_{n(j)}$ was computed by using parameters valid for the whole Lombardy Region (Tulipano, 2005; Vitullo and Federici, 2018). For each species, the authors estimated the parameters of the function starting from the data collected within the regional yield tables, and as average values of all the productivity classes. This means that, for stands characterized by different productivity classes, the value of gross increment predicted through the Richards function was the same. Since increment varies according to stand's productivity, this may represent a quite strong assumption. Nevertheless, since the information on stand's productivity was not always made available by the local FMPs, it was not possible to estimate the parameters of the Richards function for all the stands of the Case Study Area. Therefore, the only solution was to use average values already applied at the Regional level. This aspect will be further investigated to estimate the parameters of the function according to the real growth conditions of the stands of the Case Study Area. As reported in Tulipano (2005) the goodness of fit of the Richards function depends on the number of productivity classes; for a given species, as the number of productivity classes increases, R^2 between increment and volume (or mass) decreases, and vice versa.

- The parameters of the Richards function were estimated in the year 2005 starting from even older yield tables. It is reasonable to assume that, due to the increase in temperature, atmospheric CO_2 concentration and nitrogen depositions, the annual increment on the forests can be currently higher than the one of the periods in which the parameters were estimated (Tulipano, 2005).

Moreover, it should be underlined that for 425 stands (21% of the total), data on gross annual increment from the FMPs were not available (stands with insufficient accessibility or characterized by physiological-structural disorder). For all these stands, a value resulted from a weighted average from stands with similar characteristics or derived from the literature was assigned (Del Favero, 2002). All these elements affect the accuracy of the results.

For the merchantable stem mass, the validation at the stand level is currently not possible, since updated FMPs data are not available yet.

At the landscape level, the comparison between the cumulative merchantable stem mass calculated by WOCAS v2 for the year 2016 ($3.21 \cdot 10^6$ t DM; 87.37 $t \cdot ha^{-1}$ DM) and the merchantable stem mass estimated by the Mountain Community for the same year ($3.29 \cdot 10^6$ t DM; 89.54 $t \cdot ha^{-1}$ DM) shows that WOCAS v2 caused an underestimation of 2.42%. This underestimation could be further reduced if also in the FMPs calculations were performed by using the net annual increment – as in WOCAS v2 – and not the gross one. At the same time, the results could be calculated with more accuracy by also considering the natural disturbances. In conclusion, even if applying the Richards function at the stand level by using parameters valid for the Lombardy Region as a whole can cause problems of underestimation and overestimation, at the landscape level these problems compensate each other, and more accurate results can be obtained.

3.4.2 Harvested merchantable stem mass and extraction rate

For the whole analyzed period (1984-2016), the total harvested merchantable stem mass, calculated as the sum of the annual harvested mass related to each stand, reached $1.25 \cdot 10^5$ t DM (19.6% coppice; 80.4% high forest) (Figure 8), and the corresponding total C mass was $6.25 \cdot 10^4$ t C. No wood cuts occurred before 1994. Among coppices, wood cuts mainly involved: (i) *Ostrya carpinifolia* Scop. ($6.72 \cdot 10^3$ t DM; 27.5%), (ii) *Castanea sativa* Mill. ($4.67 \cdot 10^3$ t DM; 19.1%) and (iii) *Fagus sylvatica*

L. ($3.58 \cdot 10^3$ t DM; 14.6%). Among high forests, wood cuts mainly involved coniferous ($9.08 \cdot 10^4$ t DM; 90%), followed by mixed ($8.02 \cdot 10^3$ t DM; 8%) and broadleaves ($1.76 \cdot 10^3$ t DM; 2%) stands, and the main species were: (i) *Picea abies* L., (ii) *Fagus sylvatica* L. and (iii) *Larix decidua* Mill.

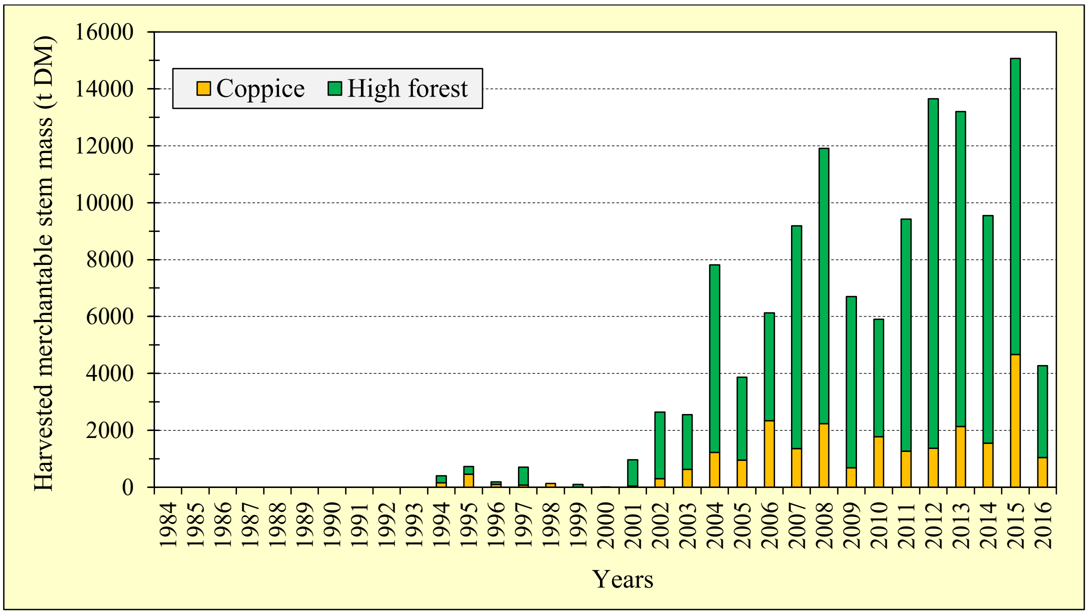

Figure 8. Harvested merchantable stem mass for coppice and high forest stands. For each year, the total value is the sum of the values related to each stand.

For a given year, the ratio between MM_{Hn} and NAI_n is called "extraction rate" (ER; -) and is one of the most important indicators for the sustainable forest management. If in the short term MM_{Hn} can exceed NAI_n (ER > 1), i.e., years characterized by a high demand of wood for energy and/or building purposes or high number of phytosanitary cuts, in the long term this condition should never occur (ER ≤ 1), to avoid the depletion of the stand's productivity over time (UNECE/FAO, 2011; Magnani and Raddi, 2014). Excluding the period 1984-1993, in which no wood cuts occurred, ER was always lower than 1, ranging from 0.03% (2000) to 31.96% (2015) (Figure 9). Wood collection should be considered as a positive event if it is performed in compliance with the principles of sustainable forest management: besides making available a renewable resource for building and energy purposes, it promotes a further increase of the annual increment and, therefore, of the C sequestration. As consequence, forests enhance their homeostatic capacity and become more resistance to natural disturbances.

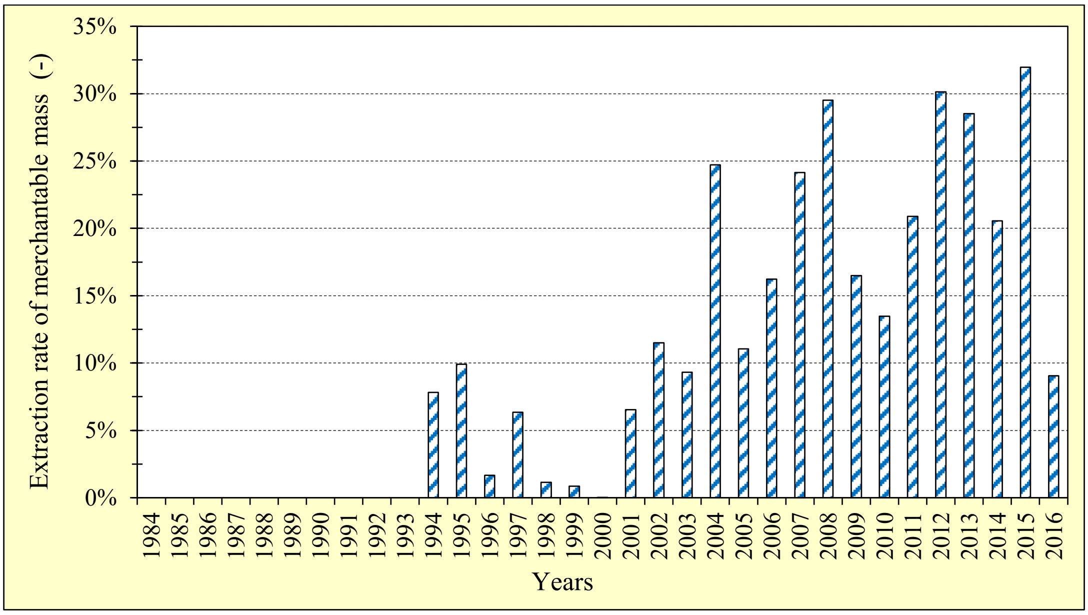

Figure 9. Extraction rate of the merchantable stem mass (no difference between coppice and high forest stands). For each year, ER is the ratio between the total harvested merchantable stem mass and the total net increment. In the period 1984-1993 no wood cuts were performed.

3.4.3 Aboveground and belowground wood biomass

Figure 10 shows the total living wood biomass (TLB_n; t DM) for each year of the analyzed period (1984-2016), calculated as the sum of AWB_n and BWB_n. In 2016 (total merchantable stem mass $MM_{2016} = 3.21{\cdot}10^6$ t DM), the living biomass was $TLB_{2016} = 5.12{\cdot}10^6$ t DM. Of this, coppices reached 14.5% ($7.42{\cdot}10^5$ t DM), whereas the remaining 85.5% ($4.38{\cdot}10^6$ t DM) was related to high forests. The total AWB and BWB (from both coppices and high forests) were $AWB_{2016} = 4.21{\cdot}10^6$ t DM (82.1%) and $BWB_{2016} = 9.17{\cdot}10^5$ t DM (17.9%).

TLB_n (t DM) increased year by year both because the extraction rate (ER; %) was always lower than 1, and because new stands (and thus, new areas) were included in the analysis (activation of new FMPs).

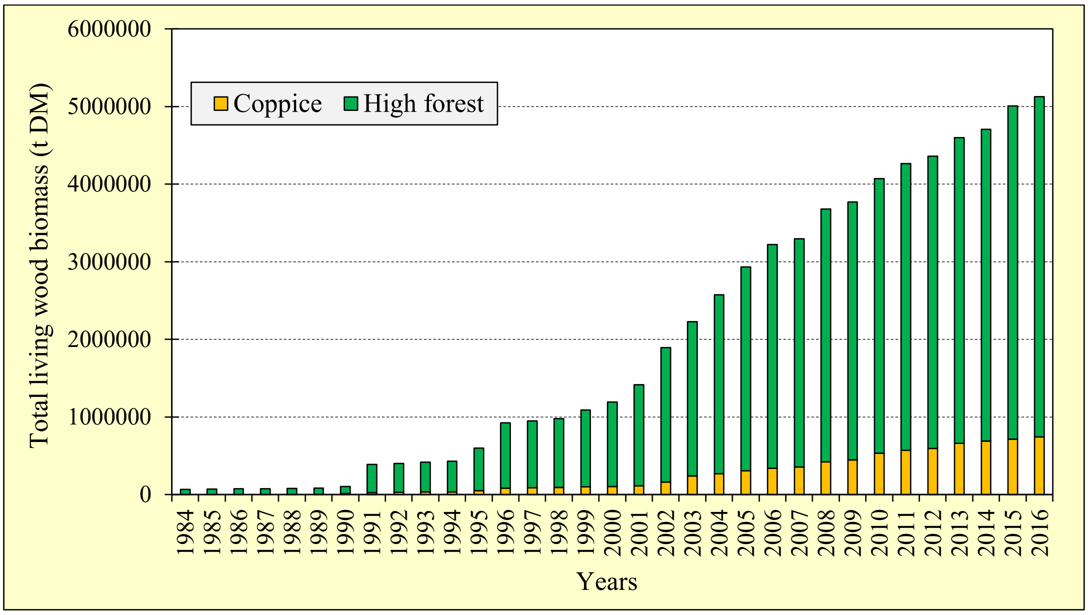

Figure 10. Living wood biomass (aboveground and belowground) for coppice and high forest stands. For each year, the total value is the sum of the values of AWB and BWB related to each stand.

Table 6 shows the weighted average yields (and the corresponding weighted standard deviations) of AWB_n, BWB_n and TLB_n for each year of the analyzed period.

Table 6. Weighted average yields (and corresponding weighted standard deviations) of aboveground wood biomass, belowground wood biomass, and total living biomass.

	Year							
	1984	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**
	($t \cdot ha^{-1} \cdot yr^{-1}$ DM)							
AWB	36.32 ± 36.28	37.76 ± 36.92	39.23 ± 37.55	40.74 ± 38.18	42.28 ± 38.81	43.86 ± 39.44	46.70 ± 36.66	60.43 ± 50.73
BWB	8.40 ± 8.16	8.74 ± 8.31	9.09 ± 8.46	9.44 ± 8.61	9.81 ± 8.76	10.18 ± 8.91	10.34 ± 8.27	13.55 ± 11.45
TLB	44.72 ± 44.42	46.50 ± 45.20	48.32 ± 45.98	50.18 ± 46.76	52.09 ± 47.54	54.04 ± 48.31	57.04 ± 44.81	73.99 ± 62.12
	Year							
	1992	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
	($t \cdot ha^{-1} \cdot yr^{-1}$ DM)							
AWB	62.62 ± 51.16	64.85 ± 51.58	67.01 ± 52.02	71.85 ± 50.83	79.82 ± 53.43	82.20 ± 53.66	84.69 ± 53.97	86.35 ± 54.60
BWB	14.03 ± 11.54	14.52 ± 11.63	14.99 ± 11.72	16.12 ± 11.46	17.79 ± 12.07	18.31 ± 12.12	18.85 ± 12.19	19.24 ± 12.31
TLB	76.65 ± 62.63	79.36 ± 63.13	82.00 ± 63.64	87.97 ± 62.18	97.60 ± 65.35	100.50 ± 65.62	103.54 ± 65.99	105.59 ± 66.73
	Year							
	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
	($t \cdot ha^{-1} \cdot yr^{-1}$ DM)							
AWB	86.60 ± 54.27	89.65 ± 55.62	83.69 ± 56.02	83.99 ± 54.82	88.21 ± 54.64	93.21 ± 55.87	94.52 ± 55.96	96.75 ± 55.91
BWB	19.33 ± 12.21	20.08 ± 12.56	18.64 ± 12.70	18.53 ± 12.42	19.48 ± 12.42	20.52 ± 12.63	20.82 ± 12.66	21.30 ± 12.65
TLB	105.93 ± 66.30	109.73 ± 68.02	102.34 ± 68.61	102.52 ± 67.09	107.69 ± 66.91	113.74 ± 68.31	115.34 ± 68.43	118.05 ± 68.36
	Year							
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
	($t \cdot ha^{-1} \cdot yr^{-1}$ DM)							
AWB	96.03 ± 56.06	98.41 ± 56.23	99.31 ± 56.55	101.65 ± 56.76	103.88 ± 56.88	106.71 ± 57.24	109.14 ± 57.30	111.88 ± 57.57

BWB	21.09 ± 12.69	21.60 ± 12.74	21.74 ± 12.78	22.23 ± 12.83	22.70 ± 12.86	23.24 ± 12.94	23.76 ± 12.96	24.39 ± 13.04
TLB	117.12 ± 68.54	120.01 ± 68.74	121.05 ± 69.07	123.88 ± 69.32	126.57 ± 69.45	129.94 ± 69.87	132.90 ± 69.92	136.27 ± 70.27

	Year
	2016
	($t \cdot ha^{-1} \cdot yr^{-1}$ DM)
AWB	114.52 ± 57.82
BWB	24.96 ± 13.10
TLB	139.48 ± 70.58

These results need to be further investigated since constant values of k_7 (biomass expansion factors) were used for each classification criteria code; this may represent a quite strong assumption, since biomass expansion factors are a very critical component for biomass estimation, and vary according to stand mass/volume, age, productivity, environmental conditions, and management (IPCC, 2006; Teobaldelli et al., 2009). The method proposed by Teobaldelli et al. (2009), and implemented into the model, is characterized by an important approximation: low stand mass is associated to low age, and vice versa; since this is not always true under real conditions, this method should be used only if the real characteristics of the stand are known. Moreover, in Teobaldelli et al. (2009), the coefficients of the non-linear function were estimated by considering several forest types grown under very different conditions across all Europe.

Therefore, to improve the accuracy of the calculations, it would be desirable that specific values of biomass expansion factors will be made available for the local conditions.

3.4.4 Dead organic matter

Figure 11 shows the DOM for each year of the analyzed period, calculated as the sum of the values related to each stand. In 2016, the dead organic matter was $DOM_{2016} = 6.21 \cdot 10^5$ t DM (12.1% TLB_{2016}). Of this, coppices reached 8.6% ($5.37 \cdot 10^4$ t DM), whereas the remaining 91.4% ($5.67 \cdot 10^5$ t DM) was related to high forests. The mass of DOM in a given year was the result of different processes, i.e., mortality due to self-thinning, production of logging residues and wood decomposition. The intensity of these processes varied year by year according to the characteristics of the stands included in the analysis.

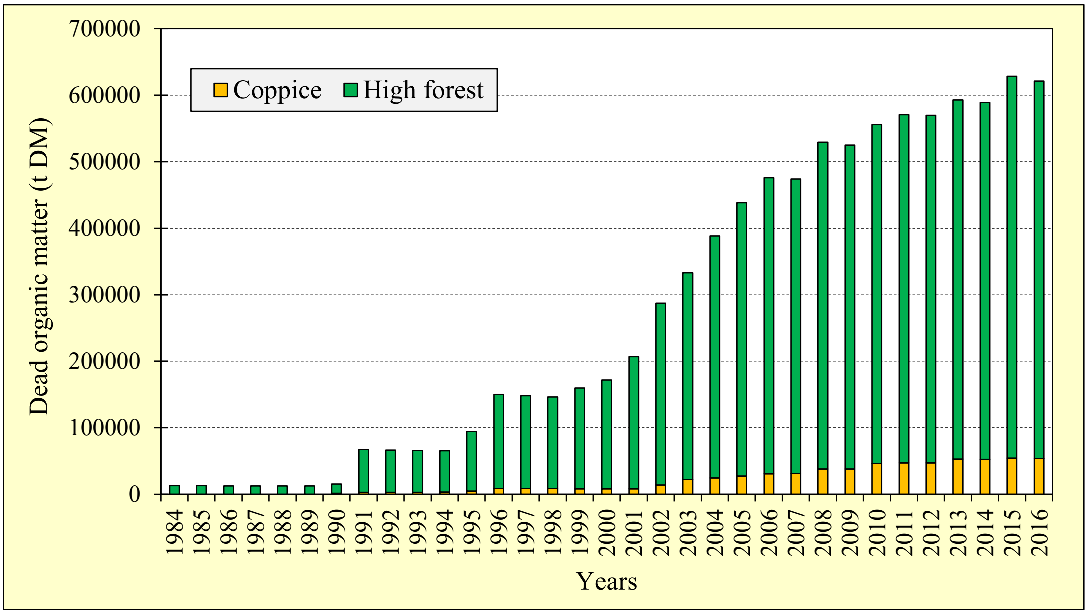

Figure 11. Dead organic matter for coppice and high forest stands. For each year, the total value is the sum of the values of the DOM related to each stand.

Table 7 shows the weighted average yields (and the corresponding weighted standard deviations) of DOM_n for each year of the analyzed period.

Table 7. Weighted average yields (and corresponding weighted standard deviations) of dead organic matter.

Year								
1984	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	
($t \cdot ha^{-1} \cdot yr^{-1}$ DM)								
8.64 ± 8.71	8.55 ± 8.52	8.47 ± 8.33	8.40 ± 8.14	8.34 ± 7.96	8.28 ± 7.79	8.34 ± 7.01	12.91 ± 12.28	
Year								
1992	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	
($t \cdot ha^{-1} \cdot yr^{-1}$ DM)								
12.74 ± 11.95	12.58 ± 11.63	12.48 ± 11.31	13.88 ± 11.28	15.88 ± 12.37	15.68 ± 12.09	15.47 ± 11.75	15.51 ± 11.67	
Year								
2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	
($t \cdot ha^{-1} \cdot yr^{-1}$ DM)								
15.25 ± 11.20	16.04 ± 11.82	15.53 ± 12.02	15.33 ± 11.52	16.25 ± 11.93	17.01 ± 12.32	17.05 ± 12.20	16.97 ± 12.04	
Year								
2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
($t \cdot ha^{-1} \cdot yr^{-1}$ DM)								
16.86 ± 12.05	16.72 ± 11.84	16.53 ± 11.61	16.57 ± 11.65	16.54 ± 11.62	16.74 ± 11.73	16.63 ± 11.55	17.11 ± 12.03	16.90 ± 11.73

These results were obtained by assuming that all the logging residues resulting from wood cuts were left inside the stands after stem collection. Although, in some cases, logging residues are extracted for energy generation, both the Regional Regulations and the Good Practices Guidelines at the national and European scale (EEA, 2006) suggest leaving residues inside the stands, since they have important environmental functions (maintenance of biodiversity, release of nutrient to the soil, reduction of soil erosion and water surface runoff) and contribute to increase the stands' productivity. Therefore, it is reasonable to suppose that, if these residues were extracted from the forests, the mass of DOM could be even considerably lower than the one calculated by this study.

3.4.5 Carbon mass

The weighted average C yields in AWB, BWB and DOM for each year of the analyzed period (C_{AWBn}; C_{BWBn}; C_{DOMn}; t·ha^{-1}·yr^{-1} C) are shown in Figure 12 and Table 8. C_{AWBn} ranged from 18.13±18.30 t·ha^{-1}·yr^{-1} C (1984) to 56.68±29.03 t·ha^{-1}·yr^{-1} C (2016); C_{BWBn} ranged from 4.19±4.12 t·ha^{-1}·yr^{-1} C (1984) to 12.37±6.62 t·ha^{-1}·yr^{-1} C (2016); finally, C_{DOMn} ranged from 4.13±3.93 t·ha^{-1}·yr^{-1} C (1989) to 8.50±6.07 t·ha^{-1}·yr^{-1} C (2015). The total C yield (C_{TOTn}) – calculated as the sum of C_{AWBn}, C_{BWBn} and C_{DOMn} – ranged from 26.63±26.80 t·ha^{-1}·yr^{-1} C (1984) to 77.45±40.19 t·ha^{-1}·yr^{-1} C (2016). The high standard deviations were caused by the presence of both stands with large areas but low mass of wood and stands with low areas but high mass of wood.

The average C yield related to the whole analyzed period (1984-2016) was 66.04 t·ha^{-1} C. Of this, C_{AWB} = 72.0%, C_{BWB} = 15.8% and C_{DOM} = 12.2%.

Decreasing of C stock in 2002 and 2003 compared to 2001 was both due to the inclusion in the calculation of new stands (activation of new FMPs) with a large area but low wood biomass, and the increase of the harvested merchantable stem mass in the other stands; on the contrary, the increase in C stock in 1991 compared to the previous years was mainly due to the inclusion of new stands characterized by a high area and a high wood biomass.

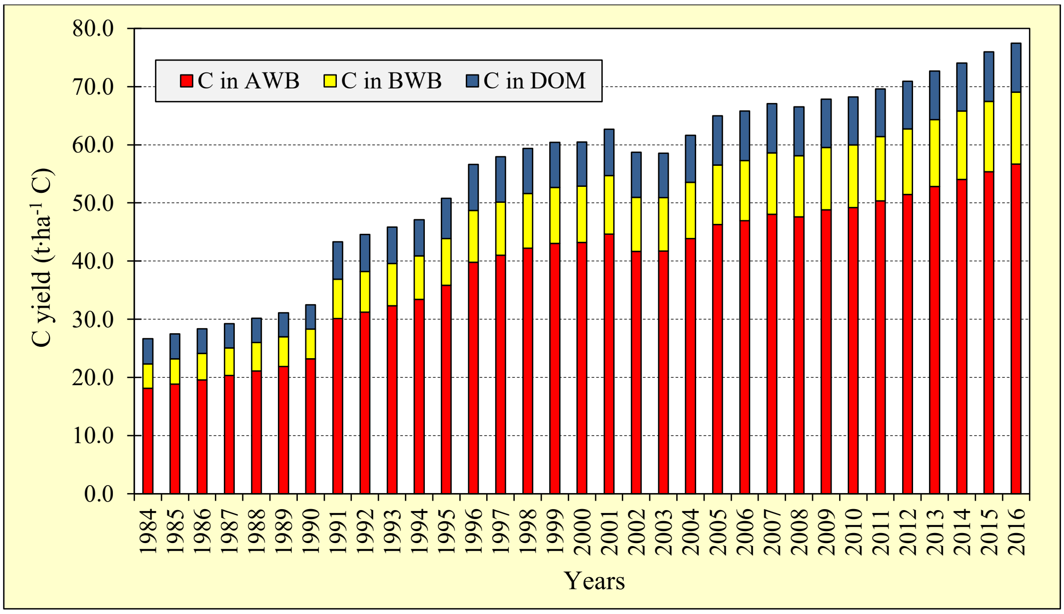

Figure 12. Weighted average C yields in AWB, BWB and DOM.

Table 8. Weighted average C yields (and corresponding weighted standard deviations) in aboveground wood biomass, belowground wood biomass, total living wood biomass, and dead organic matter. The total C yields are also reported.

	Year							
	1984	1985	1986	1987	1988	1989	1990	1991
	($t \cdot ha^{-1} \cdot yr^{-1}$ C)							
AWB	18.13 ± 18.30	18.84 ± 18.62	19.58 ± 18.94	20.33 ± 19.27	21.10 ± 19.59	21.88 ± 19.91	23.17 ± 18.47	30.13 ± 25.56
BWB	4.19 ± 4.12	4.36 ± 4.19	4.53 ± 4.27	4.71 ± 4.34	4.89 ± 4.42	5.08 ± 4.50	5.14 ± 4.18	6.76 ± 5.77
TLB	22.32 ± 22.41	23.20 ± 22.80	24.11 ± 23.20	25.04 ± 23.59	25.99 ± 23.99	26.96 ± 24.38	28.31 ± 22.59	36.90 ± 31.30
DOM	4.31 ± 4.39	4.27 ± 4.29	4.23 ± 4.20	4.19 ± 4.11	4.16 ± 4.02	4.13 ± 3.93	4.15 ± 3.54	6.45 ± 6.18
TOT	26.63 ± 26.80	27.47 ± 27.10	28.34 ± 27.40	29.23 ± 27.70	30.15 ± 28.00	31.09 ± 28.31	32.46 ± 26.10	43.34 ± 37.40
	Year							
	1992	1993	1994	1995	1996	1997	1998	1999
	($t \cdot ha^{-1} \cdot yr^{-1}$ C)							
AWB	31.22 ± 25.77	32.32 ± 25.98	33.39 ± 26.20	35.84 ± 25.63	39.80 ± 26.97	40.98 ± 27.09	42.21 ± 27.25	43.07 ± 27.56
BWB	7.00 ± 5.81	7.24 ± 5.86	7.48 ± 5.91	8.05 ± 5.78	8.88 ± 6.10	9.14 ± 6.13	9.41 ± 6.17	9.61 ± 6.23
TLB	38.22 ± 31.55	39.56 ± 31.80	40.87 ± 32.06	43.88 ± 31.36	48.68 ± 33.01	50.12 ± 33.15	51.62 ± 33.34	52.67 ± 33.70
DOM	6.36 ± 6.02	6.28 ± 5.86	6.23 ± 5.69	6.93 ± 5.69	7.93 ± 6.25	7.84 ± 6.11	7.73 ± 5.94	7.75 ± 5.90
TOT	44.58 ± 37.48	45.85 ± 37.56	47.10 ± 37.65	50.82 ± 36.89	56.61 ± 39.07	57.95 ± 39.04	59.35 ± 39.05	60.43 ± 39.35
	Year							
	2000	2001	2002	2003	2004	2005	2006	2007
	($t \cdot ha^{-1} \cdot yr^{-1}$ C)							
AWB	43.21 ± 27.37	44.66 ± 27.96	41.67 ± 28.18	41.71 ± 27.58	43.85 ± 27.52	46.29 ± 28.12	46.94 ± 28.18	48.03 ± 28.15
BWB	9.65 ± 6.18	10.01 ± 6.33	9.29 ± 6.40	9.22 ± 6.26	9.70 ± 6.27	10.21 ± 6.38	10.35 ± 6.40	10.59 ± 6.39
TLB	52.86 ± 33.47	54.67 ± 34.21	50.96 ± 34.53	50.93 ± 33.78	53.54 ± 33.73	56.50 ± 34.42	57.29 ± 34.49	58.62 ± 34.45
DOM	7.62 ± 5.66	8.00 ± 5.94	7.75 ± 6.05	7.63 ± 5.81	8.10 ± 6.02	8.47 ± 6.21	8.49 ± 6.16	8.45 ± 6.08
TOT	60.49 ± 38.85	62.68 ± 39.78	58.70 ± 40.19	58.56 ± 39.18	61.64 ± 39.28	64.97 ± 40.13	65.78 ± 40.10	67.07 ± 39.93
	Year							
	2008	2009	2010	2011	2012	2013	2014	2015
	($t \cdot ha^{-1} \cdot yr^{-1}$ C)							
AWB	47.63 ± 28.19	48.80 ± 28.27	49.20 ± 28.42	50.35 ± 28.52	51.44 ± 28.57	52.82 ± 28.75	54.01 ± 28.77	55.38 ± 28.92
BWB	10.48 ± 6.41	10.73 ± 6.43	10.79 ± 6.45	11.03 ± 6.47	11.26 ± 6.49	11.52 ± 6.53	11.78 ± 6.55	12.10 ± 6.59
TLB	58.11 ± 34.50	59.53 ± 34.60	59.98 ± 34.75	61.38 ± 34.87	62.70 ± 34.93	64.34 ± 35.14	65.79 ± 35.16	67.48 ± 35.35
DOM	8.39 ± 6.08	8.31 ± 5.97	8.21 ± 5.86	8.24 ± 5.88	8.22 ± 5.87	8.32 ± 5.92	8.26 ± 5.84	8.50 ± 6.07
TOT	66.49 ± 39.91	67.84 ± 39.85	68.20 ± 39.88	69.62 ± 39.96	70.92 ± 39.86	72.66 ± 40.08	74.06 ± 39.97	75.98 ± 40.21
	Year							
	2016							
	($t \cdot ha^{-1} \cdot yr^{-1}$ C)							
AWB	56.68 ± 29.03							
BWB	12.37 ± 6.62							
TLB	69.05 ± 35.50							
DOM	8.40 ± 5.93							
TOT	77.45 ± 40.19							

3.5 Conclusion

To support public decision-makers and local forestry authorities in forest management it is essential to develop models able to provide information related, on one hand, to the mass of stored wood and C and, on the other hand, to the mass of wood (stem, branches, and tops) that can be collected for building and energy purposes.

This study presented the methodology implemented into the model WOCAS v2 to compute the mass of stored wood and C at the stand level. Calculations were performed for different pools, i.e., aboveground wood biomass, belowground wood biomass, and dead organic matter (deadwood and litter). The main advantages of WOCAS v2 is that it uses the merchantable stem mass – that is always made available by FMPs – as the main driver for the calculations; therefore, the model can be applied in any other forest area where the same input data are available. Compared to WOCAS v1, in this second version, different improvements are introduced; the main one is the calculation of the gross annual increment of the stand through a growth function based on the merchantable stem volume without considering the age. This makes it possible to estimate the increment for both even-aged and uneven-age stands.

WOCAS v2 was tested for the first time on 2019 forest stands of Valle Camonica District (Lombardy Region, Italy) for the period 1984-2016 (45 FMPs; 37.000 ha). Even if some methodological aspects need to be improved and validation at the stand level is currently possible only for the gross annual increment, the information provided by this study can already be used to update FMPs data, and to support the sustainable forest management at the local scale.

The historical analysis of wood and C mass is crucial to compute the current mass of wood and C and to define future management practices. These might be aimed at maximizing C retention in the long life-cycle wood products, as required by the new agreements on climate change, the use of wood for energy purposes, as done by different empirical models applied at the European level (Böttcher et al., 2012), or forest C stock. In particular, C accounting for the long life-cycle products (e.g., furniture, doors, flooring, packaging, paper products, or others) can have positive implications for forest management, since it represents an important strategy to extend C stock outside the forests (Perone et al., 2015). Unlike the first commitment period of the Kyoto Protocol (2008-2012), from the second commitment period of the Protocol (2013–2020), and in the context of the current EU regulation 2018/841 for LULUCF sector (Grassi et al., 2018; Nabuurs et al., 2018), the inclusion of C accounting procedures also for wood products is mandatory (Pilli et al., 2015).

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Chapter 4 – Harvesting of wood for energy generation: a quantitative stand-level analysis in an Italian mountainous District

Partially modified from: **Nonini L.**, Fiala M. Harvesting of wood for energy generation: a quantitative stand-level analysis in an Italian mountainous District. Scandinavian Journal of Forest Research (Under review).

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Abstract: To support local forestry authorities in forest management it is crucial to develop models to provide information, on one hand, on the mass of wood and carbon (C) that forests can stock and, on the other hand, on the mass of logging residues that can be collected for energy. To do this, the first version of the model WOody biomass and Carbon ASsessment (WOCAS v1) was improved into a second version (WOCAS v2). WOCAS v2 calculates – by using data collected by Forest Management Plans (FMP) – the mass of wood ($t \cdot yr^{-1}$ of dry matter, DM) and C ($t \cdot yr^{-1}$ C) at the stand level, from the year in which the FMPs entry into force until a predefined reference year. At the same time, WOCAS v2 quantifies the mass of residues that could have been harvested for energy (potentially available logging residues; $t \cdot yr^{-1}$ DM), the potentially generated energy (heat and electricity, TE and EE, respectively; $GJ \cdot yr^{-1}$), and the potentially avoided CO_2 emissions into the atmosphere (EM; $t \cdot yr^{-1}$ CO_2) related to the final combustion process. Here it is presented the methodology used by WOCAS v2 to compute the amount of potentially available residues, generated energy and avoided CO_2 emissions. The methodology was applied to public forest stands of Valle Camonica District (Italy) collected in 45 FMPs (total area: $3.67 \cdot 10^4$ ha; period 1994-2016). The mass of residues calculated for that period was used to estimate the current sustainable supply; under the hypothesis that this mass was used, as woodchips, to feed the Organic Rankine Cycle (ORC) unit of a local centralized heating plant, TE = $2.06 \cdot 10^4 \div 2.41 \cdot 10^4$ $GJ \cdot yr^{-1}$ and EE = $5.08 \cdot 10^3 \div 5.95 \cdot 10^3$ $GJ \cdot yr^{-1}$. Moreover, assuming that: (i) heat generated by the ORC unit replaced the one produced by conventional natural gas-based heating plants and (ii) electricity generated by the ORC unit replaced the one generated by the Italian natural gas-based plants-mix (combined heat and electricity production) EM = $1.85 \cdot 10^3 \div 2.17 \cdot 10^3$ $t \cdot yr^{-1}$ CO_2.

Keywords: energy, forest stand, logging residues, wood biomass, avoided CO_2 emissions.

List of the parameters in the Text

Definition	Symbol	Unit
Wood basic density	k_1	$t \cdot m^{-3}$ of dry matter, DM
Biomass expansion factor	k_2	-
Parameter of the non-linear regression function for k_2 calculation	k_3	-
Parameter of the non-linear regression function for k_2 calculation	k_4	$t \cdot ha^{-1}$ DM
Minimum lower heating value of wood	LHV_{min}	$GJ \cdot t^{-1}$ DM
Maximum lower heating value of wood	LHV_{max}	$GJ \cdot t^{-1}$ DM
Conversion factor between GJ and tons of oil equivalent	k_5	$GJ \cdot t_{oe}^{-1}$
Average thermal efficiency of the thermal oil woodchip burners	η_{T1}	-
Average thermal efficiency of the ORC unit	η_{T2}	-
Average electric efficiency of the ORC unit	η_E	-
Average thermal efficiency of the fossil fuel-based burners	η_3	-

Lower heating value of the fossil fuel	LHV_F	$GJ \cdot m^{-3}$
Mass of emitted CO_2 per unit of fossil fuel volume	k'_{CO2}	$t \cdot m^{-3}$ CO_2
Mass of emitted CO_2 per unit of generated electricity	k''_{CO2}	$t \cdot GJ^{-1}$ CO_2

4.1 Introduction

Among the ecosystem services (ES) provided by the forests, one of the most important for climate change mitigation is wood, that can be used for energy generation, as well as the production of long life-cycle products (EASAC, 2017). The supply of wood should not compete with the provision of other ESs and should be carried out according to the principle of "cascading", that gives priority to the production of high adding value products, promoting energy conversion only if other alternatives are starting to run out (Ciccarese et al, 2014; Höglmeier et al., 2015). The principle of "cascading" is also stressed in the European Forest Strategy (European Commission, 2013), as well as in the Commission's Circular Economy package (European Commission, 2014).

Logging residues include all the wood biomass that remains in the forest after stem collection, i.e., branches and tops (IPCC, 2006; EN ISO 16559, 2014; Thiffault et al., 2014). These residues can be used for heat and electricity generation, as well as pellets for heating and liquid biofuels for transport. Moreover, there is a growing interest in using logging residues in biorefineries to develop economically viable products and chemicals as substitutes to those produced in traditional oil refineries (Palgan and McCormick, 2016). Among all these different uses, energy conversion is the most attractive and feasible solution to valorize this biomass (Smeets and Faaij, 2007; Thiffault et al., 2014).

Using wood for energy generation is often linked to the concept of "carbon neutrality": though wood may be burned in the year of harvest, its thermo-degradation does not cause additional CO_2 emissions into the atmosphere, since the emitted CO_2 was previously absorbed by trees during growth, and it will be absorbed again in the future by new trees. In contrast, the combustion of fossil fuels from geological stores causes a permanent increase of CO_2 concentration in the atmosphere (Black, 1971; IPCC, 2000). The use of residues as an energy source can promote both economic benefits, i.e., business opportunity, employments, and energy self-sufficiency for local communities (Alkan et al., 2014), and environmental advantages, i.e., reduction of fossil fuels consumption and CO_2 emissions into the atmosphere (Gan and Smith, 2007; Ranius et al., 2018). Nevertheless, it should be underlined that several authors stated that the concept of "carbon neutrality" is highly simplistic, since wood collection immediately reduces forest C stock (Routa et al., 2011).

Moreover, since wood is characterized by lower energy density and conversion efficiency compared to fossil fuels, the combustion of this biomass causes more C release into the atmosphere per unit of delivered heat or electricity compared to non-renewable resources (Agostini et al., 2014; Soimakallio et al., 2016; Norton et al., 2019). The initial increase of atmospheric C concentration causes an increase of the radiative forcing and, thus, of the global warming. As a result, an opposite effect to that expected from renewable energies can occur (Norton et al., 2019). Finally, it is critically important to recognize that the required time for these initial C emissions to be compensated by trees' growth may take decades or centuries, according to tree species and growth conditions. Therefore, the concept of "carbon neutrality" has to be evaluated case-by-case (Norton et al., 2019).

If logging residues are left in the forest, the density of the material and the risk of fire can increase, and problems of bark beetle damage and rejuvenation obstacles can emerge (Spinelli et al., 2007; Alkan et al., 2014).

On the other hand, extracting residues causes the reduction of nutrient – mainly carbon (C) and nitrogen (N) – input into deadwood, litter, and soil, decreasing forest C and N stocks (Palosuo et al., 2001; Zanchi et al., 2012). This negatively affects the stand's productivity and its future growth (Ranius et al., 2018).

Logging residues extraction is affected by environmental, ecological, economic, and logistical constraints (Hesselink, 2010; Wall and Hytönen, 2011; Kühmaier and Stampfer, 2012). Estimating the mass of available residues requires knowledge of the quantity of residues that can be produced after tree felling and the fraction that can be collected (Gan and Smith, 2006; Jurevics, 2010). In particular, to transform wood residues from a waste material into a valuable product with commercial use it is essential to consider that (Woo et al., 2019): (i) residues can be highly variable in terms of both quality (energy, water, and ash content) and quantity, and they can be widely distributed across harvesting sites; (ii) information on forest accessibility, weather conditions, availability of pre-processing technologies, haulage contracting models and energy market demand are not always easy to collect.

Biomass estimation models and direct measurements are currently the main used approach to estimate the availability of logging residues for different forest ecosystems and planning levels (Woo et al., 2019). Models are generally applied at the national/regional scale by integrating forest inventory data and allometric equations (Fehrmann and Kleinn, 2006; Morgan, 2009; Cutini et al., 2013). For example, Peltola et al. (2011) calculated the recovery rate of logging residues in stands of *Picea abies* L. in Finland by comparing the measured dry weight of residues at a power plant with the dry weight estimated at the stand level. The study was performed by using the individual trees biomass models developed by Marklund (1988) and Repola et al. (2007). In both cases, the authors used the diameter and the height of each harvested tree as input data. Models can provide high accuracy results for specific species and locations (Cutini et al., 2013); nevertheless, they are generally based on specific forest inventory data, such as tree diameters, heights, and branches size, that are not always easy to collect. On the other hand, direct measurements are carried out in sample forest harvesting sites. Trees are harvested and the weight of the components, e.g., stems, branches, and tops, are detected by using different methods, mainly according to the form of storage, scattering patterns and the type of materials. Direct field measurements are the most accurate approach to estimate logging residues; nevertheless, they are time-consuming, expensive, and can be applied at the small scale only (Woo at al., 2019).

In Italy, public forests are generally managed through Forest Management Plans (FMP), that represent *"A document that translates forest policies into a coordinated programme for a forest management unit and for regulating production, environmental and social activities for a set period of time through the use of prescriptions specifying targets, action and control arrangements"* (FAO, 1998). In Lombardy Region, guidelines for FMPs compilation were firstly introduced in 1990 and were recently updated in 2013 with the introduction of new guidelines. Each FMP is approved by the Mountain Communities – established by the law of December 3rd, 1971 – and defined as local authorities that join Alpine and pre-Alpine municipalities to improve social and economic conditions of marginalized mountainous areas of a particular territory (Dalla Valle et al., 2009). The basic management unit of each FMP is the forest stand; for each stand, the Plan describes the conditions of the forest (e.g., species, management system, function) and define the silvicultural treatments to carry out for the achievement of the management goals.

To support local forestry authorities and supply chain operators in forest management it is necessary to develop models based on FMPs data and able to provide information, on one hand, on the mass of wood and C that forests can stock and, on the other hand, on the mass of wood (stem, branches, and tops) that can be collected for building and energy purposes.

For this, the first version of the empirical model WOody biomass and Carbon ASsessment (WOCAS v1) was recently improved into a second version (WOCAS v2) (Nonini et al., 2020). WOCAS v2 calculates – by using FMPs data – the mass of wood ($t \cdot yr^{-1}$ of dry matter, DM) and carbon ($t \cdot yr^{-1}$ C) at the stand level from the year in which the FMPs entry into force until a predefined reference year. At the same time, WOCAS v2 quantifies the mass of logging residues that could have been harvested after wood cuts (potentially available logging residues; $t \cdot yr^{-1}$ DM), the potentially generated heat and electricity ($GJ \cdot yr^{-1}$), as well as the potentially avoided CO_2 emissions into the atmosphere ($t \cdot yr^{-1}$ CO_2) related to the final combustion process. This works presents the methodology implemented into WOCAS v2 to compute the amount of potentially available residues, generated energy, and avoided CO_2 emissions. The methodology was tested on public forest stands of Valle Camonica District (Lombardy Region, Italy) and preliminary results were presented.

4.2 Materials and methods

To compute the potentially available logging residues related to each stand ("j") for each year ("n") in which wood cuts occurred ($RA_{n(j)}$; $t \cdot yr^{-1}$ DM), the harvested merchantable stem mass ($MM_{Hn(j)}$; $t \cdot yr^{-1}$ DM) and the logging residues that could have been produced (producible logging residues; $RP_{n(j)}$; $t \cdot yr^{-1}$ DM) are firstly computed. In the following paragraphs it is presented the methodology implemented into WOCAS v2 to calculate the amount of potentially available logging residues, the potentially generated energy, and the potentially avoided CO_2 emissions. In the model, each stand is classified according to the following sub-criteria (SC):

- SC_1: forest structure;
- SC_2: forest function;
- SC_3: forest typology and variants;

Through the combination of these sub-criteria, the model generates, for each stand, a classification criteria code, to which specific parameters are associated. For further details about the parameters' definition, see Nonini and Fiala (2019).

4.2.1 Harvested merchantable stem mass

For each j-stand and for each year n in which wood cuts occurred, the harvested merchantable stem mass ($MM_{Hn(j)}$; $t \cdot yr^{-1}$ DM) is calculated as (IPCC, 2006):

$$MM_{Hn(j)} = MV_{Hn(j)} \cdot k_1 \quad \text{(Eq. 1)}$$

where:

$MV_{Hn(j)}$: harvested merchantable stem volume for each year in which wood cuts occurred ($m^3 \cdot yr^{-1}$).

k_1: wood basic density, i.e., ratio between wood DM and wood fresh volume ($t \cdot m^{-3}$ DM), defined for each classification criteria code.

4.2.2 Producible logging residues

The producible logging residues ($RP_{n(j)}$; $t \cdot yr^{-1}$ DM) are quantified as:

$$RP_{n(j)} = (MM_{Hn(j)} \cdot k_2) - MM_{Hn(j)} \quad \text{(Eq. 2)}$$

The parameter k_2 is the biomass expansion factor, i.e., total aboveground wood volume on merchantable stem volume (dimensionless). Assuming that k_2 is constant among the wood components, i.e., stem and branches, it can also be defined as the total aboveground wood biomass DM on merchantable stem mass DM.

$RP_{n(j)}$ can be calculated by using alternatively: (i) constant values of k_2 for each classification criteria code or (ii) variable values of k_2. In the first case, the parameter k_2 is defined for each j-stand at the beginning of the simulation and does not change over time; in the second case, the values are computed for each j-stand each year by using the method proposed by Teobaldelli et al. (2009):

$$k_{2n(j)} = k_{3(j)} + k_{4(j)}/MM^{*}_{Hn(j)} \qquad \text{(Eq. 3)}$$

where:

$MM^{*}_{Hn(j)}$ = harvested merchantable stem mass per unit of area in the year n ($t \cdot ha^{-1} \cdot yr^{-1}$ DM);

k_3, k_4 = parameters defined for each stand at the beginning of the simulation according to the corresponding classification criteria code (k_3: dimensionless; k_4: $t \cdot ha^{-1}$ DM).

4.2.3 Potentially available logging residues

For each j-stand, the potentially available logging residues ($RA_{n(j)}$; $t \cdot yr^{-1}$ DM) are calculated by taking into account a recovery rate ($\eta_{(j)}$; -), based on six availability factors: (i) stand's function; (ii) stand's management system; (iii) harvesting method; (iv) stand's accessibility; (v) forest roads' transitability and (vi) energy market demand. Each of the "m" availability factors is classified by a qualitative level that is associated to an empirical value ($v_{AF\_m(j)}$) (Table 1).

Table 1. Qualitative levels and values associated to the availability factors for recovery rate calculation.

Level of availability factor	Value
Null	0.00
Low	0.25
Medium	0.50
High	0.75
Maximum	1.00

1. Stand's function: for stands with production function, logging residues are generally used for energy purposes; the level is set on "high", since it is assumed that a fraction of the potentially available residues is left within the stand for specific ecological-environmental functions (e.g., supply of nutrients and organic matter to the soil, protection of the soil from erosion, reduction of surface water runoff and increase of biodiversity). For stands with protection, naturalistic, recreational, or other function (e.g., coppices under conversion or damaged stands to be

recovered), where the extraction of residues for energy is not the main goal, the level is set on "null", to further underline the need to leave a fraction of the potentially available residues inside the stand for the same above-mentioned reasons.

2. Stand's management system: woodchips from logging residues of coppice stands are generally used for energy generation. Therefore, for all these stands, the level is set on "maximum". Logging residues of coniferous stands have a high presence of needles and the woodchips are characterized by low quality for energy conversion processes (Grisotto, 2011). For all these stands, the level is "low". For broadleaves high forests, the level is set on "high"; finally, for mixed high forests – since it is reasonable to assume an intermediate situation between that of broadleaves high forests and coniferous high forests – the level is set on "medium".

3. Harvesting method: it depends on the wood assortment to produce and the mass of wood to be harvested. The following harvesting methods are considered: (i) Cut-to-Length (CTL), (ii) Tree Length (TL) and (iii) Full Tree (FT). In CTL, the tree is felled, delimbed and cut into different assortments directly at the felling site. This method is generally used for firewood production, and logging residues are left on the ground or subsequently collected. In TL, the tree is felled, delimbed, and the stem is extracted to the roadside, where it is cut into different assortments. Logging residues are, also in this case, left at the felling site or extracted later. In FT, the whole tree is extracted to the roadside to be processed into different assortments; no residues are generally left at the felling site (Picchio et al., 2009). In the Alpine areas, FT and FT combined with CTL are the most cost-effective solution; logging residues utilization is feasible only when integrated with roundwood production since it makes cost savings and simplified operations possible. FT is generally the most feasible harvesting method for coniferous stands, since it allows the recovery of tops, branches, and non-commercial components (Emer et al., 2011).

4. Stand's accessibility: it defines the easiness to reach the stand; WOCAS v2 is based on the classification of "accessibility" proposed by Hippoliti and Piegai (2000), recently adopted also by the Lombardy Region for the definition of the FMPs. Accessibility depends on: (i) stand's average slope ($s_{(j)}$; %), (ii) stand's horizontal distance from the nearest forest road ($d_{R(j)}$; m) and (iii) stand's difference in altitude from the nearest forest road ($d_{A(j)}$; m) (Table 2).

Table 2. Accessibility according to Hippoliti and Piegai (2000). Striped backgrounds: insufficient accessibility.

Stand's average slope	**Distance from road**				**Altitude from road**
$s_{(j)}$ (%)	$d_{R(j)}$ (m)				$d_{A(j)}$ (m)
	≤ 1000	≤ 500	≤ 250	≤ 100	
$s_{(j)} \leq 20$					-
$20 < s_{(j)} \leq 40$					≤ 100
$40 < s_{(j)} \leq 60$					≤ 100
$s_{(j)} > 60$					≤ 100

Starting from this classification – and considering that such a detailed information is not always made available by the local forestry authorities – four accessibility classes (AC) are defined in WOCAS v2:

- AC I: maximum accessibility ($s_{(j)} \leq 20\%$);
- AC II: medium-high accessibility ($20 < s_{(j)} \leq 60\%$);
- AC III: low accessibility ($s_{(j)} > 60\%$);
- AC IV: insufficient accessibility (stands falling into one of the cases identified by the cells with the striped backgrounds in Table 2).

5. Forest roads' transitability: it defines the characteristics of the roads and it is crucial to choose the type and the dimension of the transport machines. Lombardy Region (2008) proposed a classification of forest roads based on four "transitability classes" (TC), according to: (i) maximum load (l_{max}; t), (ii) minimum width (w_{min}; m), (iii) prevailing and (iv) maximum slope (s_p and s_{max}, respectively; %), and (v) minimum turning radius (tr; m) (Table 3).

Table 3. Transitability classes according to the Lombardy Region classification (2008).

TC	**Types of Machines**	**Maximum load l_{max} (t)**	**Minimum width w_{min} (m)**	**Prevailing slope (*) s_p (%)**	**Maximum slope s_{max} (%)**		**Minimum turning radius tr (m)**
					Natural Bottom	Stabilized Bottom	
I	Truck	25	3.5	≤ 10	12	16	9
II	Tractors and trailers	20	2.5	≤ 12	14	20	8
III	Small tractors	10	2.0	≤ 14	16	25	6
IV	Small vehicles	4	1.8	> 14	> 16	> 25	< 6

(*) Not overcome for at least 70÷80% along the whole road.

Starting from this classification, in WOCAS v2 two TCs are defined: (i) medium-low (combination between TC III and IV) and (ii) medium-high (combination between TC I and II).

6. Energy market demand: a high local price of fossil fuels causes a high market demand for logging residues and, therefore, an increase of their economic value. As consequence, the incentive for logging residues extraction increases, and vice versa (Steierer, 2010).

To adapt the analysis for different purposes, e.g., technical, scientific, strategic, each "m" availability factor can be associated to a "weight" ($w_{AF\_m(j)}$), computing a "weighted value" ($wv_{AF\_m(j)}$) as follows:

$$wv_{AF\_m(j)} = v_{AF\_m(j)} \cdot w_{AF\_m(j)} \quad \text{(Eq. 4)}$$

The availability factors and their corresponding qualitative levels are summarized in Table 4.

Table 4. Availability factors for recovery rate calculation.

m	Availability factor	Category	Level	Weight
1	Stand's function	Recreation	0.00 (Null)	0÷1
		Protection	0.00 (Null)	
		Other	0.00 (Null)	
		Production	0.75 (High)	
2	Stand's management system	Coniferous high forest	0.25 (Low)	0÷1
		Mixed high forest	0.50 (Medium)	
		Broadleaves high forest	0.75 (High)	
		Coppice	1.00 (Maximum)	
3	Harvesting method	Cut-to-length	0.25 (Low)	0÷1
		Tree Length	0.25 (Low)	
		Full Tree	1.00 (Maximum)	
4	Stand's accessibility	Insufficient (AC IV)	0.00 (Null)	0÷1
		Low (AC III)	0.25 (Low)	
		Medium-high (AC II)	0.75 (High)	
		Maximum (AC I)	1.00 (Maximum)	
5	Forest roads' transitability	Medium-low (TC III + IV)	0.25 (Low)	0÷1
		Medium-high (TC I + II)	0.75 (High)	
6	Energy market demand	Limited	0.25 (Low)	0÷1
		Good	0.50 (Medium)	
		Consistent	1.00 (Maximum)	

$\eta_{(j)}$ is calculated as the sum of the weighted values associated to each factor:

$$\eta_{(j)} = \sum_{m \to 1}^{6} wv_{AF\_m(j)} \quad \text{(Eq. 5)}$$

$\eta_{(j)}$ is computed at the beginning of the simulation and is assumed as constant over time. Then, for each j-stand, $RA_{n(j)}$ is quantified as:

$$\mathrm{RA}_{\mathrm{n(j)}} = \mathrm{RP}_{\mathrm{n(j)}} \cdot \eta_{\mathrm{(j)}} \quad \text{(Eq. 6)}$$

The annual producible residues (RP_n; t·yr^{-1} DM) are quantified as the sum of the producible residues of each stand. In the same way, the annual potentially available residues (RA_n; t·yr^{-1} DM) are calculated as the sum of the potentially available residues of each stand. Therefore, the annual cumulative recovery rate (η_n; -) is computed as:

$$\eta_{\mathrm{n}} = \frac{\mathrm{RA}_{\mathrm{n}}}{\mathrm{RP}_{\mathrm{n}}} \quad \text{(Eq. 7)}$$

Unlike $\eta_{(j)}$, η_n can vary over time since, year-by-year, new stands with different characteristics can be included in the analysis.

4.2.4 Wood energy equivalent and potentially generated energy

The potentially generated heat and electricity (GJ·yr^{-1}) related to the annual mass of available residues are computed by assuming that wood is used, as woodchips, to feed an Organic Rankine Cycle (ORC) unit of a centralized heating plant. First of all, the annual energy equivalent related to this biofuel (EQ_n; GJ·yr^{-1}; t_{oe}·yr^{-1}) is computed by assuming a range in the lower heating value of wood (LHV_{min} and LHV_{max}, respectively; GJ·t^{-1} DM) and a conversion factor k_5 = 41.86 GJ·t_{oe}^{-1}:

$$\mathrm{EQ}_{\mathrm{n}_{\mathrm{min;max}}} = \mathrm{RA}_{\mathrm{n}} \cdot \mathrm{LHV}_{\mathrm{min;max}} \quad \text{(Eq. 8)}$$

$$\mathrm{EQ}_{\mathrm{n}_{\mathrm{min;max}}} = (\mathrm{RA}_{\mathrm{n}} \cdot \mathrm{LHV}_{\mathrm{min;max}})/\mathrm{k}_5 \quad \text{(Eq. 9)}$$

The annual potentially generated heat (TE_n; GJ·yr^{-1}) and electricity (EE_n; GJ·yr^{-1}) are then calculated as:

$$\mathrm{TE}_{\mathrm{n}_{\mathrm{min;max}}} = \mathrm{RA}_{\mathrm{n}} \cdot \mathrm{LHV}_{\mathrm{min;max}} \cdot \eta_{\mathrm{T1}} \cdot \eta_{\mathrm{T2}} \quad \text{(Eq. 10)}$$

$$\mathrm{EE}_{\mathrm{n}_{\mathrm{min;max}}} = \mathrm{RA}_{\mathrm{n}} \cdot \mathrm{LHV}_{\mathrm{min;max}} \cdot \eta_{\mathrm{T1}} \cdot \eta_{\mathrm{E}} \quad \text{(Eq. 11)}$$

where:

η_{T1} = average thermal efficiency of the thermal oil woodchip burners (-);

η_{T2} = average thermal efficiency of the ORC unit (-);

η_E = average electric efficiency of the ORC unit (-).

4.2.5 Potentially avoided CO_2 emissions into the atmosphere

The annual potentially avoided CO_2 emissions related to the final combustion process are calculated by assuming that:

- heat generated by the ORC unit replaced the one produced by conventional fossil fuel-based heating plants;

- electricity generated by the ORC unit replaced the one produced by fossil fuel-based plants.

The annual potentially avoided CO_2 emissions related to heat (EM'_n; $t \cdot yr^{-1}$ CO_2) replacement are computed as:

$$EM'_{n_{min;max}} = V_{F\_n_{min;max}} \cdot k'_{CO2} = [TE_{n_{min;max}} / (LHV_F \cdot \eta_{T3})] \cdot k'_{CO2} \quad \text{(Eq. 12)}$$

The annual potentially avoided CO_2 emissions related to electricity (EM''_n; $t \cdot yr^{-1}$ CO_2) replacement are quantified as:

$$EM''_{n_{min;max}} = EE_{n_{min;max}} \cdot k''_{CO2} \quad \text{(Eq. 13)}$$

where:

$V_{F\_n_{min;max}}$ = minimum and maximum volume of the substituted fossil fuel ($m^3 \cdot yr^{-1}$);

LHV_F = lower heating value of the fossil fuel ($GJ \cdot m^{-3}$);

η_{T3} = average thermal efficiency of the fossil fuel-based burners (-);

k'_{CO2}= emission factor (mass of emitted CO_2 per unit of fossil fuel volume; $t \cdot m^{-3}$ CO_2);

k''_{CO2} = emission factor (mass of emitted CO_2 per unit of generated electricity; $t \cdot GJ^{-1}$ CO_2).

The total potentially avoided CO_2 emissions (EM_n; $t \cdot yr^{-1}$ CO_2) related to the use of the local woodchips in the ORC unit are computed as:

$$EM_{n_{min;max}} = EM'_{n_{min;max}} + EM''_{n_{min;max}} \quad \text{(Eq. 14)}$$

4.3 Case Study

Valle Camonica is characterized by a total forest area of $A_F = 6.58 \cdot 10^4$ ha. Public forests (managed through FMPs) reach 64.1% of A_F, whereas private forests (not managed through FMPs) represent the remaining 35.9%.

For each j-stand, data on: (i) forest structure, (ii) forest function, (iii) forest typology and variants, (iv) area (ha) and (v) harvested merchantable stem volume for each year in which cuts occurred ($MV_{Hn(j)}$; $m^3 \cdot yr^{-1}$) were extracted through queries from the "Cadastral FMPs database" (CPA v2; Microsoft Access format) made available by the Mountain Community.

Overall, data related to 2019 forest stands registered in 45 FMPs (total area: $3.67 \cdot 10^4$ ha) were collected, covering the period between 1984 (starting year of the oldest FMP) and 2016 (more recent available data from the CPA v2).

For both coniferous and broadleaves high forests, $MV_{Hn(j)}$ refers to the volume of the stem over bark from stump (30 cm above the forest floor) up to a top diameter of 7 cm of living trees with a diameter at breast height (1.3 m above the forest floor) higher than 17.5 cm, excluding branches and foliage. For all the broadleaves high forests, the volume is estimated by using the diameter-height relations for *Fagus sylvatica* L. valid for the Lombardy Region; for coniferous, specific diameter-height relations defined for the Trentino-Alto-Adige Region for the main species are used. For coppices, $MV_{Hn(j)}$ is generally estimated at the forest road by measuring the volume of the trailer used for transport. In some cases, this volume can also include branches, but since the CPA v2 does not specify when this occurs, it was assumed that also for coppices $MV_{Hn(j)}$ referred to the volume of the stem only.

For high forests, data on age was made available by the CPA v2 only for 10% of the stands; for coppices, data on the average age was made available only for 17.5% of the stands. In all the other cases, data were not made available, both because no measurements were carried out by the technicians (stands characterized by insufficient accessibility or high physiognomic-structural disorder) and because stands were uneven-aged.

According to the common classification adopted for Italian forests (Del Favero, 2002), the 2019 stands are characterized by 66 forest typologies, aggregated into 12 forest categories according to the main species (Table 5).

Table 5. Forest categories according to the main species: stands' number and area.

Forest category	Main species	Stands (n.)	Stands (ha)
1	*Picea abies* L.	1125 (55.7%)	19506.4 (53.1%)
2	*Larix decidua* Mill.	356 (17.6%)	8288.0 (22.6%)
3	*Alnus viridis* Chaix D.C., *Betula* L., *Corylus avellana* L.; *Sorbus aucuparia* L., other species with high physiognomic-structural disorders	185 (9.2%)	3617.4 (9.8%)
4	*Fraxinus ornus* L., *Ostria carpinifolia* Scop., *Quercus pubescens* Willd.	112 (5.5%)	1838.5 (5.0%)
5	*Castanea sativa* Mill.	63 (3.1%)	860.6 (2.3%)
6	*Picea abies* L. and *Fagus sylvatica* L.	45 (2.2%)	646.5 (1.8%)
7	*Fagus sylvatica* L.	41 (2.0%)	584.6 (1.6%)
8	*Quercus robur* L.	29 (1.4%)	459.2 (1.2%)
9	*Acer pseudoplatanus* L., *Tilia cordata* Mill., *Fraxinus ornus* L.	26 (1.3%)	414.4 (1.1%)
10	*Abies alba* Mill.	24 (1.2%)	340.5 (0.9%)
11	*Pinus sylvestris* L.	8 (0.4%)	111.3 (0.3%)
12	*Pinus montana* Mill; *Robinia pseudoacacia* L.	5 (0.2%)	74.4 (0.2%)
	Total	2019 (100%)	36741.8 (100%)

Table 6 shows management system, forest functions, stands' number, and area.

Table 6. Management systems, forest functions, stands' number, and area.

Management system	Function	Family	Stands			
			Number	Area		
				Total	min÷max	Average ± s.d[a]
			(-)	(ha)	(ha)	(ha)
High forest	Production	Coniferous	1063 (52.6%)	17480.9 (47.6%)	1.4÷50.0	16.4±7.6
		Broadleaves	7 (0.3%)	97.6 (0.3%)	7.5÷25.3	13.9±6.3
		Mixed	96 (4.8%)	1615 (4.5%)	3.8÷45.0	16.8±8.5
	Protection	Coniferous	445 (22.0%)	10816.3 (29.4%)	2.2÷110.0	24.3±14.8
		Broadleaves	4 (0.2%)	44.2 (0.1%)	8.6÷14.0	11.1±2.2
		Mixed	20 (1.0%)	356.4 (1.0%)	2.0÷38.6	17.8±9.7
	Recreational	Coniferous	25 (1.2%)	641.3 (1.7%)	6.2÷49.8	25.7±11.2
	Other	Coniferous	7 (0.3%)	38.4 (0.1%)	1.3÷14.2	5.5±5.0
		Broadleaves	7 (0.3%)	117.4 (0.3%)	5.5÷35.7	16.8±10.0
Coppice	Production	Broadleaves	196 (9.7%)	3191.5 (8.7%)	1.3÷65.5	16.3±9.5
	Protection		73 (3.6%)	1328.9 (3.6%)	0.8÷96.0	18.2±16.4
	Recreational		5 (0.2%)	78.9 (0.2%)	2.4÷32.5	15.8±15.3
	Other		71 (3.5%)	934.9 (2.5%)	2.3÷34.8	13.2±7.2
Total	-	-	2019 (100%)	36741.8 (100%)	0.8÷110.0	18.2±10.9

Note: [a] standard deviation.

Up to now, all the logging residues currently available from the public forest stands of the District are used in the local centralized heating plant of Ponte di Legno. The plant is equipped with three different units (Table 7): (i) district heating, (ii) cogeneration, more recently installed and consisting in an ORC system to produce both heat and electricity, and (iii) back-up unit.

Table 7. Description of the technical characteristics of the centralized heating plant of Ponte di Legno. Heat and electricity are generated by using woodchips coming from both regional and non-regional forests (40% and 60%, respectively) (Source: interview to the head of the technical office).

Technical characteristics	Description
District heating unit (starting year of activity: 2009)	
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	$8.63 \cdot 10^3$ t ($4.92 \cdot 10^3$ t DM); 7966 h
Cogeneration energy unit (ORC) (starting year of activity: 2017)	
Woodchips burners (heat transfer fluid: thermal oil)	1
Burner nominal thermal power; Average thermal efficiency (η_{T1})	4.04 MW; 0.75
ORC nominal thermal power; Average thermal efficiency (η_{T2})	2.95 MW; 0.73
ORC nominal electric power; Average electric efficiency (η_E)	0.73 MW; 0.18
Year 2019: woodchips consumption; Operating time	$1.34 \cdot 10^4$ t ($7.65 \cdot 10^3$ t DM); 8121 h
Thermal back-up unit (starting year of activity: 2009)	
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

To calculate the harvested merchantable stem mass, different values of k_1 were used for each classification criteria code, starting from the values proposed by Giordano (1980) for Italian forest species. To calculate the producible logging residues, different values of k_2 were used for each classification criteria code, adopting the values reported in Federici et al. (2008).

Even if six availability factors were defined and the proposed methodology is able to consider all the factors simultaneously for each stand, for a preliminary assessment, $\eta_{(j)}$ was computed by taking into account only the factor 1 (stand's function) and 2 (stand's management system) and the same weight coefficient ($w_{AF\_1(j)} = w_{AF\_2(j)} = 0.5$) was assigned. Since the analysis focused on a past scenario assessment, detailed stand-level information for the other factors was not available yet at the time of the study.

To quantify the wood energy equivalent and the potentially generated heat and electricity, an average value of LHV_{min} and LHV_{max} equal to 17.5 and 20.5 $GJ \cdot t^{-1}$ DM, respectively, was assumed (Fiala, 2012). For η_{T1}, η_{T2} and η_E, the same values as the ones reported in Table 7 for the centralized heating plant of Ponte di Legno were adopted. The potentially avoided CO_2 emissions into the atmosphere were computed by assuming that:

- heat generated by the ORC unit replaced the one produced by conventional heating plants powered with natural gas, which is the most used fossil fuel in the District for heat generation;

- electricity generated by the ORC unit replaced the one produced by the Italian natural gas-based plants-mix for combined heat and electricity production and distributed through the National grid.

The following values were used: (i) $LHV_F = 3.53 \cdot 10^{-2}$ $GJ \cdot m^{-3}$ (standard conditions), (ii) $k'_{CO2} = 1.97 \cdot 10^{-3}$ $t \cdot m^{-3}$ CO_2 (Italian Ministry for the Environment, 2018) and (iii) $k''_{CO2} = 9.81 \cdot 10^{-2}$ $t \cdot GJ^{-1}$ CO_2 (National Environmental Information System, 2018).

4.4 Results and discussion

4.4.1 Wood cuts, cut area and harvested merchantable stem mass

Wood was harvested 4333 times in 1215 stands (60% of the total stands extracted from the CPA v2) in the period 1994-2016. This period was characterized by five phases (Figure 1): (i) starting (1994-2000), with a low number of cuts (54 in seven years); (ii) considerable intermediate increase (2001-2007), in which the number of cuts raised from 73 to 317, except for 2005, in which the number decreased; (iii) stabilization (2008-2011); (iv) new increase (2012-2014), with the highest number of cuts (1142, 26% of the total) and a peak in 2013 and (v) a last decrease (2015-2016), in which the number of cuts was lower compared to the previous phase (301 and 145 for the year 2015 and 2016, respectively).

One of the main reasons for this great variability in the annual harvested merchantable mass was probably the age structure of the forests and differences in the past wood market trend. Nevertheless, since data on stand's age were made available by the CPA v2 only for 10% of high forests and for 17.5% of coppices, and detailed information on the past market trend was not available, these results need to be further investigated.

The increase in cuts number in the second and fourth phases (2001-2007, excluding 2005, and 2012-2014, respectively) was mainly due to: (i) possible increase in the number of cuts in existing FMPs and (ii) activation of new FMPs and execution of cuts on new stands.

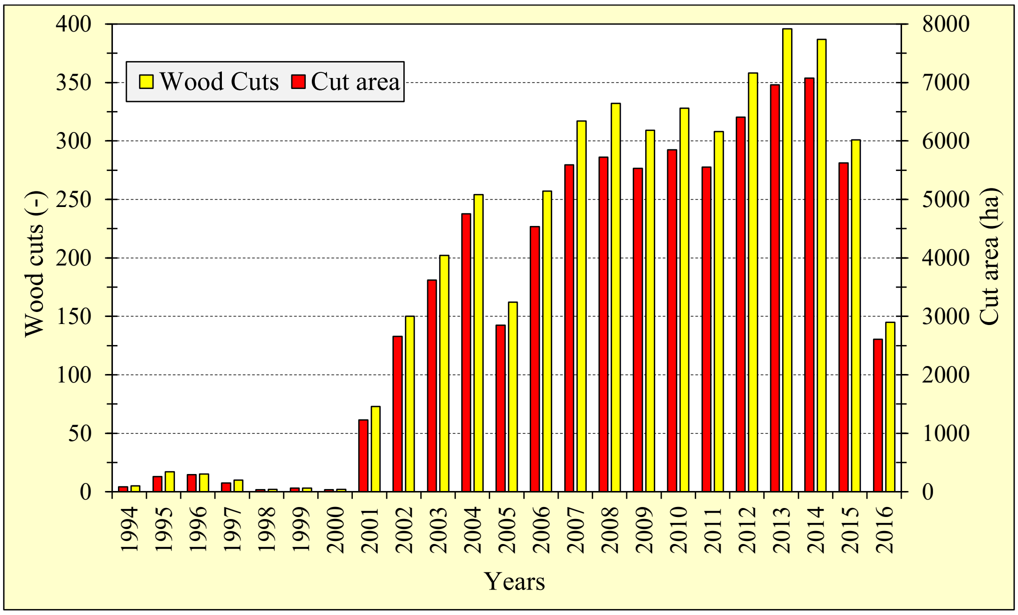

Figure 1. Wood cuts (left axis) and corresponding cut area (right axis). For each year, the total values are the sum of the values related to each stand.

Figure 2 shows the annual MM_H for each year of the analysis. For the whole period (1994-2016), the total harvested merchantable stem mass – calculated as the sum of the annual harvested mass in each stand – was $MM_{Htot} = 1.25 \cdot 10^5$ t DM (19.6% coppice; 80.4% high forest) and the weighted average value was 1.61 $t \cdot ha^{-1}$ DM.

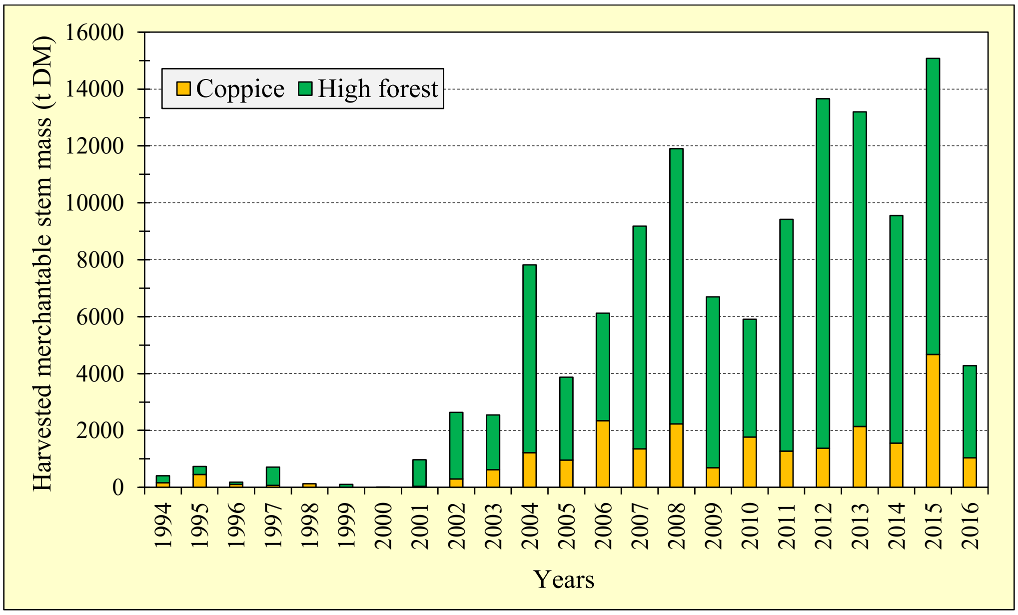

Figure 2. Harvested merchantable stem mass for coppice and high forest stands. For each year, the total value is the sum of the values related to each stand.

By comparing Figure 1 and Figure 2, the following considerations can be made:

1. in the intermediate increase phase, 2005 was characterized by the lowest number of cuts, cut area, and harvested merchantable stem mass (MM_H);

2. 2009, 2010, 2011 and 2014 were characterized by several wood cuts on large areas with low MM_H;

3. in 2015, despite the number of cuts and cut area were similar to that of the years 2009-2011, MM_H was the highest of the whole analyzed period ($1.51 \cdot 10^4$ $t \cdot yr^{-1}$ DM). This was mainly due to improvements in: (i) forestry mechanization and (ii) management of logging companies;

4. 2016 was characterized by a strong reduction of the number of cuts, cut area and MM_H, probably due to missing data in the CPA v2.

Pending specific experimental values, to have a projection of the currently harvested merchantable stem mass (2017-2020), it was reasonable to consider – under the hypothesis that in the period 2011-2015 forests were sustainably managed and had a specific age structure and mean tree volume – an average value equal to the one calculated for that period, i.e., $1.22 \cdot 10^4 \pm 2.55 \cdot 10^3$ $t \cdot yr^{-1}$ DM. This is a simplification that can be acceptable only for a limited period of time, in which it is reasonable to assume that natural disturbances do not occur, and forests maintain similar characteristics in terms of total volume, productivity and silvicultural treatments.

4.4.2 Producible and potentially available logging residues

For the whole analyzed period, the total mass of RP and RA, calculated as the sum of the annual RP and RA related to each stand, were $RP_{tot} = 4.04 \cdot 10^4$ t DM (26.7% coppice; 73.3% high forest) and $RA_{tot} = 2.25 \cdot 10^4$ t DM (36.4% coppice; 63.6% high forest), respectively; the weighted average values were 0.52 $t \cdot ha^{-1}$ DM and 0.29 $t \cdot ha^{-1}$ DM for RP and RA, respectively. The trends of RP and RA were similar to that of the merchantable stem mass: in the first part of the period (1994-2000), RP and RA were considerably lower compared to the subsequent years. The highest values occurred in 2015 ($4.95 \cdot 10^3$ $t \cdot yr^{-1}$ DM for RP and $3.10 \cdot 10^3$ $t \cdot yr^{-1}$ DM for RA).

Figure 3 shows the potentially available logging residues within the analyzed period for coppice and high forest stands.

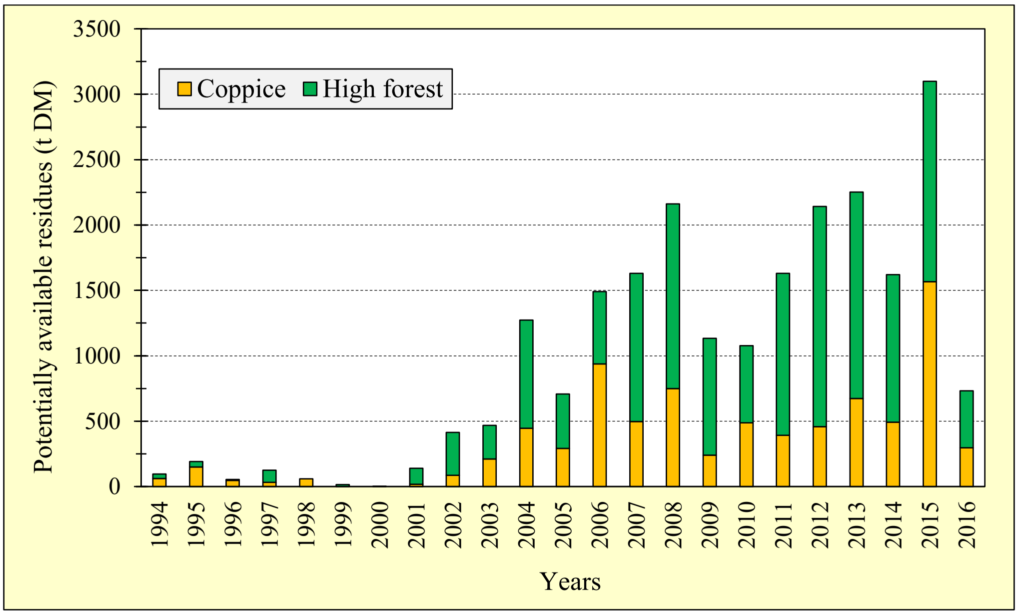

Figure 3. Potentially available logging residues for coppice and high forest stands. For each year, the total value is the sum of the values related to each stand.

The assumption of a constant value of the parameter k_1 (wood basic density) for each classification criteria code is a simplification, since the wood basic density is affected not only by forest typology and forest structure, but also by age, growth rate, stand's productivity, environment conditions and silvicultural treatments, e.g., fertilization and thinning (Lundgren, 2004; Oliva et al., 2006; Ikonen et al., 2008; Zhang et al., 2012). Variation of wood basic density can also occur among trees of the same species under similar environmental conditions (Messier et al., 2010). Despite all these aspects should be considered to improve the accuracy of the results, the above-mentioned simplification can be acceptable considering the large period of time that characterized the study and that WOCAS v2 uses the single stand as the basic functional unit.

Moreover, despite the values of k_1 used in the study were published almost 40 years ago, they were specific for Italy and were the only ones available for all the species. To reduce the uncertainty in biomass and logging residues estimation, it would be desirable that more recent values related to regional or local conditions were made available.

Another aspect that needs to be discussed is the use of the parameter k_2 (biomass expansion factor). Using a constant value of biomass expansion factor for each classification criteria code may represent a quite strong assumption, since the biomass expansion factor varies according to environmental conditions, stand's productivity, age, volume/mass and silvicultural treatments. Nevertheless, it should be noted that the method proposed by Teobaldelli et al. (2009) and implemented into the model for the calculation of this parameter assumes that a low stand mass corresponds to a low age, and vice versa; since this not always occur under real conditions, this method should be used only if the real characteristics of the stand are known.

4.4.3 Recovery rate of producible logging residues

As mentioned before, the annual cumulative recovery rate (η_n) can change over time, since year-by-year new stands with different characteristics can be included in the analysis. For the whole analyzed period, the average recovery rate, calculated as the ratio between RA_{tot} and RP_{tot} is 55.8%, ranging from a minimum of 48.6% (2001) to a maximum of 87.5% (1998) (Figure 4).

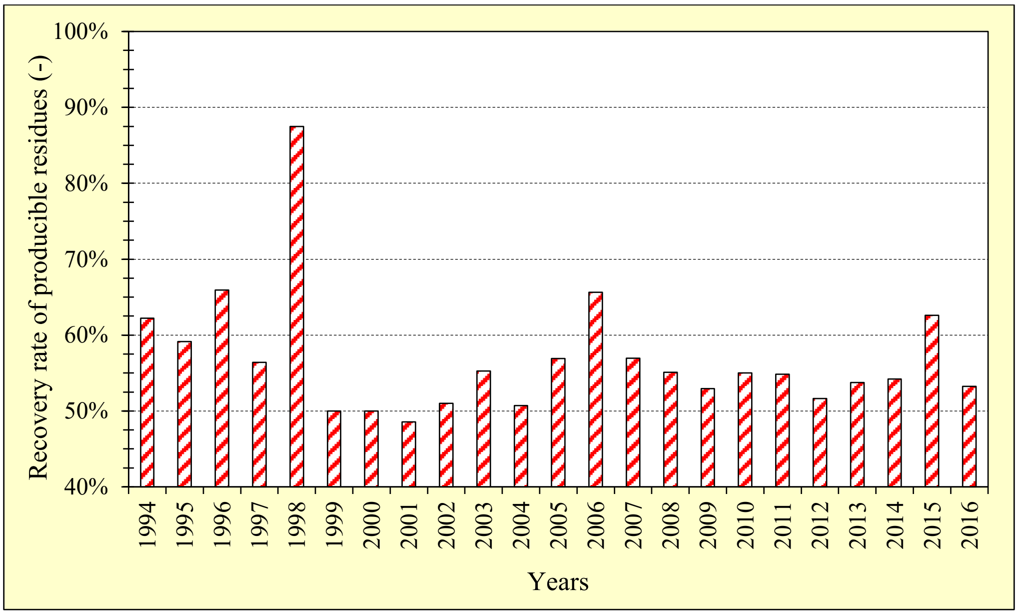

Figure 4. Recovery rate of the producible logging residues. For each year, the value is the ratio between the total potentially available residues and the total producible residues calculated for all the stands.

The stand recovery rate is defined at the beginning of the simulation and is considered as constant over time; moreover, as mentioned before, the rate was computed only by considering the availability factor 1 (stand's function) and 2 (stand's management system). A more in-depth analysis is currently in progress and is based on the use of georeferenced FMPs data and a Digital Elevation Model (DEM; spatial resolution of 30 m) processed with Geographic Information System (GIS) software. Therefore, it is reasonable to assume that the mass of potentially available residues calculated through the GIS analysis can be even considerably different from the one provided by this study.

Since $RA_{n(j)}$ were computed starting from $MM_{Hn(j)}$, also for logging residues, as a first approximation, it was reasonable to assume that the currently harvested mass ($t \cdot yr^{-1}$ DM) was constant after the last years of the analysis to date, and equal to the average value calculated for the period 2011-2015, i.e., $2.15 \cdot 10^3 \pm 6.04 \cdot 10^2$ $t \cdot yr^{-1}$ DM.

4.4.4 Harvested merchantable stem mass and logging residues yields

The weighted average yields (and the corresponding standard deviations) of MM_H, RP and RA are shown in Table 8. The harvested merchantable stem yield ($t\cdot ha^{-1}\cdot yr^{-1}$ DM) reached the highest value in 1994 (4.73 ± 3.22 $t\cdot ha^{-1}\cdot yr^{-1}$ DM) due to low cuts number on small areas and low MM_H, and the highest standard deviation in 2015 (2.68 ± 10.52 $t\cdot ha^{-1}\cdot yr^{-1}$ DM) due to cuts on similar areas (25 ha, approximately) with high variation in MM_H ($0.2\div3.0\cdot10^3$ $t\cdot yr^{-1}$ DM).

The minimum average yields of RP and RA were reached in 2000 (0.03 ± 0.06 $t\cdot ha^{-1}\cdot yr^{-1}$ DM and 0.02 ± 0.19 $t\cdot ha^{-1}\cdot yr^{-1}$ DM, respectively), whereas the maximum yields occurred in 1998 (2.10 ± 0.36 $t\cdot ha^{-1}\cdot yr^{-1}$ DM and 1.84 ± 1.34 $t\cdot ha^{-1}\cdot yr^{-1}$ DM, respectively).

Table 8. Weighted average yields (and corresponding weighted standard deviations) of harvested merchantable stem mass, producible and potentially available logging residues.

	Year							
	1994	1995	1996	1997	1998	1999	2000	2001
	($t\cdot ha^{-1}\cdot yr^{-1}$ DM)							
MM_H	4.73 ± 3.22	2.79 ± 4.57	0.63 ± 1.63	4.72 ± 6.50	3.96 ± 0.67	1.65 ± 1.20	0.12 ± 0.22	0.79 ± 3.41
RP	1.82 ± 1.07	1.23 ± 2.02	0.28 ± 0.85	1.49 ± 1.91	2.10 ± 0.36	0.48 ± 0.34	0.03 ± 0.06	0.23 ± 0.99
RA	1.13 ± 4.36	0.73 ± 7.26	0.19 ± 5.15	0.84 ± 5.45	1.84 ± 1.34	0.24 ± 1.10	0.02 ± 0.19	0.11 ± 2.96
	Year							
	2002	2003	2004	2005	2006	2007	2008	2009
	($t\cdot ha^{-1}\cdot yr^{-1}$ DM)							
MM_H	0.99 ± 3.14	0.70 ± 1.60	1.65 ± 4.48	1.36 ± 3.50	1.35 ± 3.73	1.64 ± 4.00	2.08 ± 4.34	1.21 ± 3.93
RP	0.31 ± 0.94	0.23 ± 0.59	0.53 ± 1.44	0.44 ± 1.09	0.50 ± 1.65	0.51 ± 1.25	0.69 ± 1.44	0.39 ± 1.22
RA	0.16 ± 2.88	0.13 ± 2.25	0.27 ± 5.26	0.25 ± 3.63	0.33 ± 7.67	0.29 ± 4.57	0.38 ± 4.86	0.20 ± 3.83
	Year							
	2010	2011	2012	2013	2014	2015	2016	
	($t\cdot ha^{-1}\cdot yr^{-1}$ DM)							
MM_H	1.01 ± 1.74	1.70 ± 3.68	2.13 ± 5.79	1.90 ± 3.33	1.35 ± 2.95	2.68 ± 10.52	1.64 ± 4.22	
RP	0.33 ± 0.63	0.53 ± 1.13	0.65 ± 1.70	0.60 ± 1.06	0.42 ± 0.91	0.88 ± 3.36	0.53 ± 1.47	
RA	0.18 ± 2.15	0.29 ± 3.67	0.33 ± 5.24	0.32 ± 3.45	0.23 ± 3.00	0.55 ± 13.9	0.28 ± 5.76	

4.4.5 Wood energy equivalent, potentially generated energy and avoided CO_2 emissions

The EQ associated to the sustainable mass of residues ($2.15\cdot10^3\pm6.04\cdot10^2$ $t\cdot yr^{-1}$ DM) was EQ_n = $3.76\cdot10^4\div4.40\cdot10^4$ $GJ\cdot yr^{-1}$ ($8.98\cdot10^2\div1.05\cdot10^3$ $t_{oe}\cdot yr^{-1}$); the potentially generated energy (heat and electricity), the potentially avoided natural gas consumption and CO_2 emissions are shown in Table 9 and Figure 5.

Table 9. ORC unit of Ponte di Legno plant: potentially generated energy, potentially avoided natural gas consumption and CO_2 emissions into the atmosphere related to the use of local logging residues.

Type	Potentially generated energy	Potentially avoided natural gas consumption	Potentially avoided CO_2 emissions
	($GJ \cdot yr^{-1}$)	($m^3 \cdot yr^{-1}$) (std. conditions)	($t \cdot yr^{-1}$ CO_2)
Heat	$2.06 \cdot 10^4 \div 2.41 \cdot 10^4$	$6.86 \cdot 10^5 \div 8.03 \cdot 10^5$ [a]	$1.35 \cdot 10^3 \div 1.58 \cdot 10^3$ [c]
Electricity	$5.08 \cdot 10^3 \div 5.95 \cdot 10^3$	$2.46 \cdot 10^5 \div 2.88 \cdot 10^5$ [b]	$4.99 \cdot 10^2 \div 5.84 \cdot 10^2$ [d]
Total	-	$9.31 \cdot 10^5 \div 1.09 \cdot 10^6$	$1.85 \cdot 10^3 \div 2.17 \cdot 10^3$

Notes: [a] average thermal efficiency of household burners (natural gas): 0.85; [b] average specific consumption of plants-mix for heat and electricity generation (natural gas): 6143 $kJ \cdot kWh^{-1}$ of gross electricity (Source: TERNA, 2018); [c] average emission factor (natural gas): $1.972 \cdot 10^{-3}$ $t \cdot m^{-3}$ CO_2 (Source: Italian Ministry for the Environment, 2018); [d] average emission factor of plants-mix for heat and electricity generation (natural gas): $9.81 \cdot 10^{-2}$ $t \cdot GJ^{-1}$ CO_2 (gross electricity) (Source: National Environmental Information System, 2018).

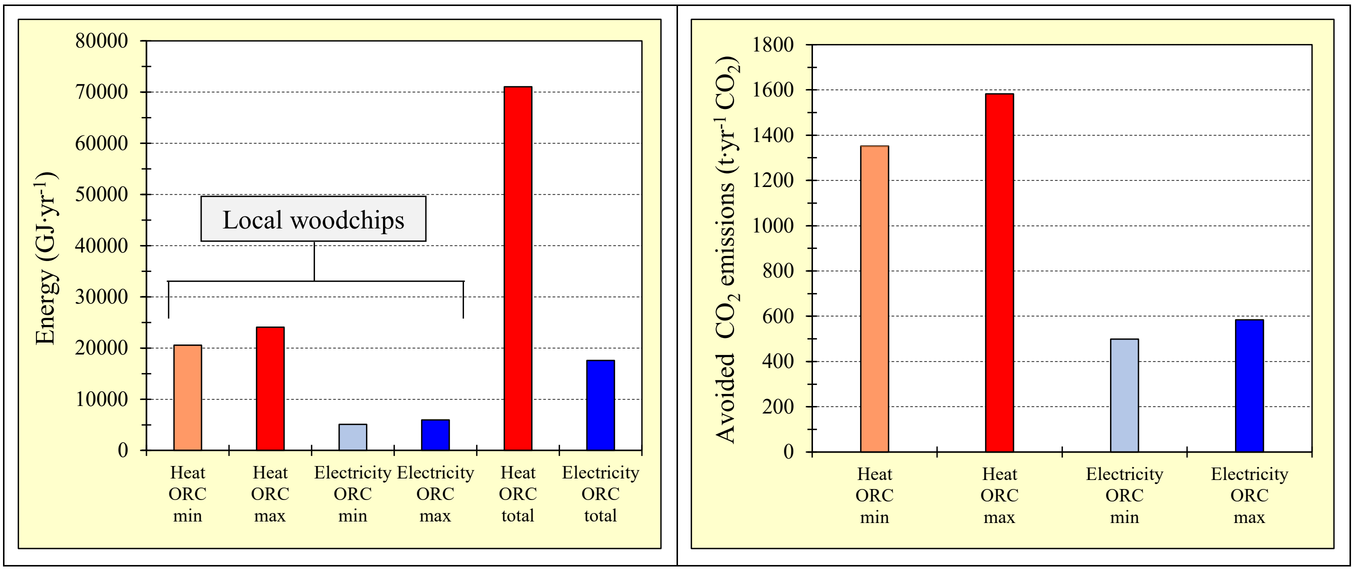

Figure 5. Ponte di Legno ORC unit (reference year: 2019): left side: (i) potentially generated heat (min-max) and electricity (min-max) from the local woodchips ($2.15 \cdot 10^3$ $t \cdot yr^{-1}$ DM) and total generated heat and electricity from wood coming from both regional and non-regional forests ($7.65 \cdot 10^3$ $t \cdot yr^{-1}$ DM); right side: potentially avoided CO_2 emissions into the atmosphere related to the use of the local woodchips.

If the ORC unit was fed by using only the local logging residues – considering the operating time of this unit related to the year 2019 (8121 $h \cdot yr^{-1}$) – the potentially generated heat and electricity would represent, at most, only 34% of the heat and electricity actually generated by the unit (Figure 5). In other words, the thermal and electric power (0.82 MW and 0.20 MW, respectively) would be much lower than the nominal ones, with an average power load of the ORC unit equal to 28%. For this reason, the plant of Ponte di Legno is actually also fed with roundwood woodchips coming from both local and non-local forests.

Moreover, among the benefits for the local economy associated to the use of local woodchips for energy cogeneration, the natural gas otherwise purchased for thermal energy production has to be considered. By assuming an average gross price of this fossil fuels equal to 0.90 €·m^{-3}, the local economic value related to the potentially avoided natural gas consumption would be equal to $6.17 \cdot 10^5 \div 7.22 \cdot 10^5$ €·yr^{-1}. Although the potentially avoided natural gas consumption related to electricity generation was calculated ($2.46 \cdot 10^5 \div 2.88 \cdot 10^5$ m^3·yr^{-1}), the corresponding economic and environmental benefits cannot be allocated to the Valle Camonica only, but need to be distributed throughout the whole national territory (i.e., energy and environmental bills).

4.5 Conclusion

The analysis of wood supply is essential to evaluate the availability of this resource at different space and time scales and its possible utilization. This study presented the methodology implemented into the model WOCAS v2 to estimate the mass of logging residues that could have been harvested from the public forest stands of a given territory, from the years in which the FMPs entry into force until a predefined reference year. The methodology also allows to estimate the potentially generated heat and electricity under the assumption that the residues were prepared into woodchips to feed the ORC unit of a centralized heating plant.

The methodology was tested for the first time for the public forest stands (45 FMPs; 37000 ha) of Valle Camonica (Lombardy Region, Italy); the potentially available logging residues were calculated for the period between 1994 (year in which the first wood cut occurred) and 2016 (more recent available data from the local FMPs); according to the past trend, the current sustainable mass of residues was estimated. Then, under the hypothesis that this mass was used, as woodchips, to feed the ORC unit of the centralized heating plant of Ponte di Legno, the potentially generated heat and electricity and the corresponding potentially avoided CO_2 emissions into the atmosphere related to the final combustion process were computed, by assuming that wood substituted non-renewable energy sources. Even if the results provided by this study were preliminary and the described methodology is currently under improvement, the results can be of interest for the local community, since they were obtained from the first use of the local FMPs data in a model specifically developed to compute the stored mass of forest wood and C and the mass of available residues for energy generation.

Further efforts are needed to collect: (i) FMPs data for the years after 2016, as it concerns the harvested merchantable stem mass and (ii) information on the currently harvested mass of logging residues to validate the results, that up to now is not possible since no official measured (primary) data at the stand-level are available.

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Chapter 5 – Assessment of forest logging residues availability for energy production by using a Geographic Information System (GIS)

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Abstract: Using biomass for energy can help to reduce the dependence on non-renewable energy sources, limit the pressure on the environment and promote the transition into low-carbon emission economies. In heavily forested regions, such as the Italian Alps, one of the main renewable energy sources is wood, and in particular logging residues, that include branches and tops that remain inside the forests after stem collection. This paper presents the methodology implemented into the second version of the model WOody biomass and Carbon ASsessment (WOCAS v2) to calculate the potentially available logging residues ($t \cdot yr^{-1}$ dry matter, DM), the potentially generated heat and electricity ($GJ \cdot yr^{-1}$) and the potential avoided CO_2 emissions into the atmosphere ($t \cdot yr^{-1}$ CO_2) related to wood combustion only, under the hypothesis that wood substitutes non-renewable energy sources. In WOCAS v2, the mass of potentially available residues is computed by multiplying the mass of residues that could have been produced after tree felling for a recovery rate based on different availability factors, i.e.: stand's function, stand's management system, harvesting method, stand's accessibility, forest roads' transitability and energy market demand. The methodology was applied for public forests of Valle Camonica District (Italy) for the period 2009-2016. The stand's accessibility and the forest roads' transitability were computed by combining FMPs data coming from WOCAS v2 with a Digital Elevation Model (DEM) in GIS software. The mass of potentially available residues computed for the analyzed period was then used to quantify the current sustainable supply. The potentially generated heat and electricity and the avoided CO_2 emissions were calculated by assuming that the current supply of residues was used as woodchips to feed the Organic Rankine Cycle (ORC) unit of a local centralized heating plant.

Keywords: availability factors, energy, geographic information system, logging residues, topographic features.

List of the parameters in the Text

Definition	Symbol	Unit
Wood basic density	k_1	$t \cdot m^{-3}$ of dry matter, DM
Biomass expansion factor	k_2	-
Parameter of the non-linear regression function for k_2 calculation	k_3	-
Parameter of the non-linear regression function for k_2 calculation	k_4	$t \cdot ha^{-1}$ DM
Minimum lower heating value of wood	LHV_{min}	$GJ \cdot t^{-1}$ DM
Maximum lower heating value of wood	LHV_{max}	$GJ \cdot t^{-1}$ DM
Conversion factor between GJ and tons of oil equivalent	k_5	$GJ \cdot t_{oe}^{-1}$
Average thermal efficiency of the thermal oil woodchip burners	η_{T1}	-
Average thermal efficiency of the ORC unit	η_{T2}	-
Average electric efficiency of the ORC unit	η_E	-
Lower heating value of the fossil fuel	LHV_F	$GJ \cdot m^{-3}$
Average thermal efficiency of the fossil fuel-based burners	η_{T3}	-
Mass of emitted CO_2 per unit of fossil fuel volume	k_6	$t \cdot m^{-3}$ CO_2
Mass of emitted CO_2 per unit of generated electricity	k_7	$t \cdot GJ^{-1}$ CO_2

5.1 Introduction

Biomass plays a strategic role in energy production, reducing the impacts of pollution on the environment. Producing energy from biomass is a responsible way to address the environmental and energetic challenges and offset greenhouse gases (GHG) emissions from fossil fuels (Cozzi et al., 2013).

In 2005, biomass represented the biggest source of renewable energy in the EU-25, accounting for 66%, approximately. Of this, wood amounted to 89%. In 2012, the total supply of wood for energy in EU was about 1 billion m^3, corresponding to 8500 PJ. Of this volume, about 70% was forest wood, whereas the remaining 30% was non-forest wood (Hetsch et al., 2008).

Different types of wood can be used for energy generation (Ferranti, 2014): (i) industrial residues, i.e., wood residues resulting from industrial processing, (ii) logging residues, i.e., wood left inside the forest after stem collection, such as branches and tops (IPCC, 2006; EN ISO 16559, 2014; Thiffault et al., 2014), (iii) complementary fellings, i.e., the difference between the maximum sustainable harvestable volume of the merchantable stem and the current harvested volume needed to satisfy the market demand, (iv) short rotation forestry plantations, (v) wood from trees outside forests and (vi) recycled wood.

Logging residues, industrial residues and short rotation forestry plantations represent the most important sources for solid fuels production. Stems from complementary fellings can also be a source of energy; nevertheless, this utilization is often in competition with other uses, e.g., building purposes (Karjalainen et al., 2004).

Different options are available to generate energy from logging residues: (i) direct combustion for heat generation, (ii) repackaging of biomass in pellets to use for private heating and (iii) co-firing in central district heating plants for the production of both heat and electricity through the combined heat and power technology (CHP) (Faaij, 2006).

If logging residues are left in the forest, the density of the biomass and the risk of fire can increase, with the result that rejuvenation obstacles and bark beetle damage can occur (Spinelli et al., 2007; Alkan et al., 2014).

On the other hand, extracting logging residues can cause a loss of biodiversity through habitat homogenisation and a more intensive soil disturbance (Humphrey et al., 2004, Schuck et al., 2004; EEA, 2006). At this purpose, it is recommended to leave a fraction of residues inside the forest as deadwood, since it is essential for biodiversity (Humphrey et al., 2004; Schuck et al., 2004). However, there are also some coniferous man-made forestry plantations that are not thinned due to lack of market demand and low prices. In these cases, wood thinning can provide an opportunity to reduce the density of the forest, making available space for trees' growth and regeneration and, as a result, improving the habitat value for several species (EEA, 2006).

Wood removal always results in the reduction of nutrient input into deadwood, litter, and soil (Palosuo et al., 2001; Zanchi et al., 2012), causing the decrease of the stand's productivity and growth (Ranius et al., 2018). It is generally assumed that no problems related to stand's productivity occur when extracting residues from sustainably managed forests (EEA, 2006), even if attention should be paid for poor sites, such as peatlands, if no compensatory fertilization is carried out after wood collection (Sverdrup and Rosen, 1998).

Wood extraction also increases soil exposure to wind and rainwater, and thus the risk of erosion and water run-off (EEA, 2006). Modern logging technologies should consider measures to reduce soil compaction and erosion; as a good management practice, tree roots should be left into the soil and a fraction of the available branches should be used as "mats" on extraction machines to protect the soil. This would place a limit on the maximum rate of biomass extraction (EEA, 2006).

A better understanding of the factors affecting the variability of logging residues recovery rate is crucial to support the policy development for a sustainable forest biomass procurement (Thiffault et al., 2014). Several jurisdictions developed policies and guidelines to ensure the ecological sustainability of logging residues recovery (Abbas et al., 2011). Such policy and guidelines are often based on expert judgement to define the sustainable recovery rate of residues, also by defining suitable and unsuitable areas, as well as the amount of biomass to be left on site (Thiffault et al., 2014).

To further limit the pressure on the environment, no intensive wood use should occur in protected forest areas managed for conservation purposes. The legal constraints for these areas vary from a total ban on management to no limitations for sustainable management, where only low-impact management is allowed. This is particularly important for Southern Europe, where lots of forests are under the Natura 2000 network (EEA, 2006).

The mass of available residues depends on: (i) the mass of residues that are produced after tree felling, which in turn depends on the mass of the harvested merchantable stem (EEA, 2006; Gan and Smith, 2006; Jurevics, 2010); (ii) environmental, ecological, economic, and logistical constraints, such as the characteristics of the forest roads, characteristics and morphology of the landscape, as well as the used machines and technologies (UNECE/FAO, 2007; Schmithüsen and Hirsch, 2010; Wall and Hytönen, 2011; Kühmaier and Stampfer, 2012; Zambelli et al., 2012; Sacchelli et al., 2013).

Using forest management models and Geographic Information Systems (GIS) software is an optimal solution to compute the mass of available residues, since through the GIS analysis is it possible to collect useful data that are generally not made available by the local Forest Management Plans (FMP).

For this work, studies concerning logging residues availability assessment through GIS were investigated by performing a systematic literature searching procedure. Two queries were defined: (i) TITLE-ABS-KEY (forest AND residue AND gis) and (ii) TITLE-ABS-KEY (assess* AND forest AND residue AND gis). By merging the queries results, 107 papers were obtained; to take into consideration a source, criteria based on the type of publication (on international journals) were followed; conference proceedings and book chapters in English were considered case by case. For this study, only 44 papers were considered.

The research items that were found according to the systematic literature searching procedure (Schillaci et al., 2018) were analyzed to build a robust pipeline to define: (i) spatial scale, (ii) environmental variables and (iii) modelling approach. The SCOPUS search derived from the two queries were merged in a MS Office Excel spreadsheet that reports the general bibliometric information (e.g., authors, title, journal, year, abstract), to which site-specific information (e.g., characteristics of the studied area, used geodata, considered research paper) were added. The analysed 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 treated in one paper. Most of the papers mainly focused on the location of a biomass power plant (Viana et al., 2010; Abreu et al., 2020; Pergola et al., 2020; Van Holsbeeck and Srivastava, 2020) followed by the implementation of a decision support system and studies aimed at the assessment of the availability of forest biomass at different scales (Yoshioka and Sakai, 2005; Frombo et al., 2009; Rørstad et al., 2010; Zambelli et al., 2012; Quinta-Nova et al., 2017; Geri et al., 2018; Zyadin et al., 2018). Nonetheless, a consistent part of the literature aimed at the estimation of the cost-effectiveness of biomass collection (i.e., harvesting and transport) (Cozzi et al., 2013; Nakahata et al., 2014; Lundmark et al., 2015; Laitila et al., 2016; Athanassiadis and Nordfjell, 2017; Guilhermino et al., 2018; Cintas et al., 2018).

This paper presents the methodology implemented into the second version of the model WOody biomass and Carbon ASsessment (WOCAS v2) (Nonini et al., 2020) to calculate the mass of potentially available logging residues ($t \cdot yr^{-1}$ dry matter, DM), the potentially generated heat and electricity ($GJ \cdot yr^{-1}$) and the avoided CO_2 emissions into the atmosphere ($t \cdot yr^{-1}$ CO_2) associated to the final combustion process, under the assumption that logging residues are used for heat and electricity generation instead of non-renewable resources. The described methodology was tested for the Valle Camonica District (Lombardy Region, Italy) and results were discussed.

5.2 Materials and methods

In WOCAS v2, each stand (“j”) is classified through three sub-criteria (SC):

- SC_1: forest structure;
- SC_2: forest function;
- SC_3: forest typology and variants;

By combining these sub-criteria, WOCAS v2 generates, for each stand, a classification criteria code, to which specific parameters are associated. For further details about the parameters' definition, see Nonini and Fiala (2019).

Calculation are performed from the year in which the FMPs entry into force until a predefined reference year. Starting from data collected by FMPs, WOCAS v2 firstly calculates the mass of residues that could have been produced for each j-stand and for each year ("n") in which wood cuts occurred (producible logging residues; $RP_{n(j)}$; $t \cdot yr^{-1}$ DM). The mass of the potentially available logging residues ($RA_{n(j)}$; $t \cdot yr^{-1}$ DM) is calculated by taking into account different availability factors. Under the hypothesis that residues are prepared into woodchips to feed an Organic Rankine Cycle (ORC) unit of a centralized heating plant, the potentially generated heat and electricity ($GJ \cdot yr^{-1}$), as well as the potentially avoided CO_2 emissions into the atmosphere ($t \cdot yr^{-1}$ CO_2) related to the final combustion process are estimated by assuming that:

- heat generated by the ORC unit replaced the one produced by conventional fossil fuel-based heating plants;

- electricity generated by the ORC unit replaced the one generated by fossil fuel-based plants.

5.2.1 Producible logging residues

For each j-stand and for each year n in which wood cuts occurred, the producible logging residues ($RP_{n(j)}$; $t \cdot yr^{-1}$ DM) are computed as (IPCC, 2006):

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

where:

$MV_{Hn(j)}$: harvested merchantable stem volume for each j-stand and for each year n;

k_1: wood basic density, i.e., ratio between wood DM and wood fresh volume ($t \cdot m^{-3}$ DM), defined in the model for each classification criteria code;

k_2: biomass expansion factor, i.e., total aboveground wood volume on merchantable stem volume. Under the assumption that k_2 does not vary among wood components, it can also be expressed as the total aboveground wood biomass DM on merchantable stem mass DM.
To improve the flexibility of WOCAS v2, $RP_{n(j)}$ can be calculated by using, alternatively: (i) constant values of k_2 for each classification criteria code or (ii) variable values of k_2. In this second case, the values of k_2 are quantified for each j-stand each year, as follows (Teobaldelli et al., 2009):

$$k_{2n(j)} = k_{3(j)} + k_{4(j)}/MM^{*}_{Hn(j)} \quad \text{(Eq. 2)}$$

where:
$MM^{*}_{Hn(j)}$ = harvested merchantable stem mass per unit of area in the year n ($t \cdot ha^{-1} \cdot yr^{-1}$ DM);
k_3, k_4 = parameters of the non-linear regression function, defined at the beginning of the simulation for each classification criteria code (k_3: dimensionless; k_4: $t \cdot ha^{-1}$ DM).

5.5.2 Potentially available logging residues

The mass of potentially available logging residues ($RA_{n(j)}$; $t \cdot yr^{-1}$ DM) is calculated by considering a recovery rate ($\eta_{(j)}$; -) based on six availability factors:

- stand's function;
- stand's management system;
- harvesting method;
- stand's accessibility;
- forest roads' transitability;
- energy market demand.

Each of the "m" availability factors is classified by a qualitative level defined by an empirical value ($v_{AF\_m(j)}$) that reduces the mass of the potentially available logging residues (Table 1).

Table 1. Qualitative levels of the availability factors and corresponding empirical values.

Levels	Empirical value
Null	0.00
Low	0.25
Medium	0.50
High	0.75
Maximum	1.00

1. Stand's function: stands with production function are managed to use wood along the supply chain and the recovery of logging residues is generally maximized for the production of woodchips for energy generation; for all these stands, the level is set on "high"; it is assumed that a fraction of the available residues is left in the forest to regulate the water flow, prevent soil erosion, increase biodiversity, release nutrient into the soil and increase the stand's productivity (EEA, 2006). For stands with protection function (i.e., stands managed for both indirect protection against hydrogeological risk and water flows, and direct protection against soil erosion, landslides, wildfires, and avalanches), naturalistic function (i.e., stands managed to increase animal's and plant's biodiversity), recreational function, or stands whose function is classified as "other" (e.g., coppices under conversion or damaged stands to be recovered), since the extraction of residues for energy purposes is not the mail goal, the level is set on "null", to further underline that residues should be left on site for the same above-mentioned reasons.

2. Stand's management system: In the Italian Alps, logging residues of coppice stands are generally used for energy production. Therefore, for all these stands, the level is set on "maximum". Logging residues of coniferous generally have a high presence of needles and, as a result, the produced woodchips are characterized by a low quality for energy conversion processes (Grisotto, 2011). Therefore, for all these stands, the level is set on "low". For broadleaves high forests, the level is set on "high"; finally, for mixed high forests – by assuming an intermediate situation between that of broadleaves high forests and coniferous – the level is "medium".

3. Harvesting method: it defines the form through which wood is delivered to the forest road and depends on the amount of wood to be processed and the assortment to produce. Different harvesting methods can be applied for wood extraction (Picchio et al., 2009; Emer et al., 2011): (i) Cut-to-length (CTL), (ii) Tree Length (TL), and (iii) Full Tree (FT). In the CTL method, the operations of felling, delimbing, debarking (if necessary), and sectioning into predetermined length are performed at the felling site; the stem is cut in length of 1–7 m and is extracted to the forest roads. The final length of the wood depends on the industrial utilization of the material, as well as the characteristics of the used machines (Pereira Castro et al., 2016). This method causes an incomplete exploitation of wood residues, since only the tops can be effectively recovered, whereas branches generally remain at the felling site (Spinelli et al., 2006). When the mass of residues to be collected is high enough to justify the increase of the working times and of the production factors, an additional step can be performed to also collect the branches. However, especially in the Alpine conditions, this further step is often quite complex and not economically

sustainable. The CTL method is widely applied since it allows a low level of mechanization and more manual, motor-manual, or animal-assisted operational steps (Malinovski and Malinovski, 1998). Leaving logging residues at the felling site also protects soil from erosion. Moreover, damages on the remaining trees and soil compaction may be reduced compared to the other harvesting methods (Malinovski and Malinovski, 1998). Considering all these elements, the qualitative level associated to the CTL method is "low". In the TL method, the felled tree is delimbed at the felling site and the stem is delivered to the forest road in length higher than 7 m. The stem is sectioned into predefined length in a separate processing step beside forest road or in an intermediate log yard. Like the CTL method, logging residues generally remain at the felling site (Pereira Castro et al., 2016). Therefore, also for this method, the qualitative level is "low". The FL method consists in collecting the full tree, i.e., stem, branches, and tops, but without roots and tree stump, that are left inside the stand. Further processing is performed at intermediate log yards, landing zone, or forest roads. The FT method is generally adopted when a high mass of logging residues is potentially available for energy generation and can be easily extracted, or when the forest floor must be cleared of all the produced residues (Thees et al., 2011; Pereira Castro et al., 2016). Considering all these elements, the qualitative level associated to the FT method is "maximum". The negative aspects of the FT method are: (i) the extreme nutrient extraction, (ii) driving with heavy machines all over the area, and (iii) the unprotected soil exposed to wind and rainfall.

4. Stand's accessibility: it is defined as the easiness to reach the stand, and influences both type and dimension of forestry machines to use. According to Hippoliti and Piegai (2000), the accessibility depends on: (i) stand's average slope ($s_{(j)}$; %), (ii) stand's horizontal distance from the forest road ($d_{R(j)}$; m) and (iii) stand's difference in altitude from the forest road ($d_{A(j)}$; m) (Table 2).

Table 2. Accessibility according to Hippoliti and Piegai (2000). Striped backgrounds: insufficient accessibility.

Stand's average Slope	**Distance from road**				**Altitude from road**
$s_{(j)}$ (%)	**$d_{R(j)}$ (m)**				**$d_{A(j)}$ (m)**
	≤ 1000	**≤ 500**	**≤ 250**	**≤ 100**	
$s_{(j)} \leq 20$					-
$20 < s_{(j)} \leq 40$					≤ 100
$40 < s_{(j)} \leq 60$					≤ 100
$s_{(j)} > 60$					≤ 100

For the calculation, four accessibility classes (AC) are defined:

- AC IV: insufficient accessibility;

- AC III: low accessibility ($s_{(j)} > 60\%$);
- AC II: medium-high accessibility ($20 < s_{(j)} \leq 60\%$);
- AC I: maximum accessibility ($s_{(j)} \leq 20\%$);

The qualitative levels associated to the abovementioned ACs are: (i) null, (ii) low, (iii) high, and (iv) maximum, for AC IV, AC III, AC II and AC I, respectively.

5. Forest roads' transitability: it expresses the characteristics of the forest roads used for transport. In Lombardy Region, forest roads are classified through four "transitability classes" (TC) (Lombardy Region, 2008) according to (Table 3):

- maximum load (l_{max}; t);
- minimum width (w_{min}; m);
- prevailing and maximum slope (s_p and s_{max}, respectively; %);
- minimum turning radius (tr; m).

Table 3. Transitability classes of forests roads (Lombardy Region, 2008).

TC	**Types of machines**	**Maximum load l_{max} (t)**	**Minimum width w_{min} (m)**	**Prevailing slope [a] s_p (%)**	**Maximum slope s_{max} (%)**		**Minimum turning radius tr (m)**
					Natural bottom	Stabilized Bottom	
I	Truck	25	3.5	≤ 10	12	16	9
II	Tractors and trailers	20	2.5	≤ 12	14	20	8
III	Small tractors	10	2.0	≤ 14	16	25	6
IV	Small vehicles	4	1.8	> 14	> 16	> 25	< 6

Note: [a] not overcome for at least 70÷80% along the whole road.

For the calculation, two TCs are defined:

- medium-low (combination between TC III and IV);
- medium-high (combination between TC I and II);

The qualitative levels associated to the above-mentioned TCs are: (i) low and (ii) high for the TC "medium-low" and "medium-high", respectively.

6. Energy market demand: a high local price of fossil fuels causes a high demand for residues and, therefore, their economic value increases. As a result, the extraction of residues is encouraged, and vice versa (Steierer, 2010). This availability factor is subdivided into the following three

categories: (i) limited, (ii) good and (iii) consistent, and the corresponding qualitative levels are: (i) low, (ii) medium and (iii) maximum, respectively.

The user has to associate a "weight" to each of the "m" availability factors ($w_{AF\_m(j)}$), and a "weighted value" ($wv_{AF\_m(j)}$) is then computed:

$$wv_{AF\_m(j)} = v_{AF\_m(j)} \cdot w_{AF\_m(j)} \quad \text{(Eq. 3)}$$

Table 4 shows the availability factors and the corresponding qualitative levels.

Table 4. Availability factors for the calculation of the recovery rate.

m	Availability factor	Category	Level	Weight
1	Stand's function	Recreation	0.00 (Null)	0÷1
		Protection	0.00 (Null)	
		Other	0.00 (Null)	
		Production	0.75 (High)	
2	Stand's management system	Coniferous high forest	0.25 (Low)	0÷1
		Mixed high forest	0.50 (Medium)	
		Broadleaves high forest	0.75 (High)	
		Coppice	1.00 (Maximum)	
3	Harvesting method	Cut-to-length	0.25 (Low)	0÷1
		Tree Length	0.25 (Low)	
		Full Tree	1.00 (Maximum)	
4	Stand's accessibility	Insufficient (AC IV)	0.00 (Null)	0÷1
		Low (AC III)	0.25 (Low)	
		Medium-high (AC II)	0.75 (High)	
		Maximum (AC I)	1.00 (Maximum)	
5	Forest roads' transitability	Medium-low (TC III + IV)	0.25 (Low)	0÷1
		Medium-high (TC I + II)	0.75 (High)	
6	Energy market demand	Limited	0.25 (Low)	0÷1
		Good	0.50 (Medium)	
		Consistent	1.00 (Maximum)	

$\eta_{(j)}$ is quantified as the sum of the weighted values of each availability factor:

$$\eta_{(j)} = \sum_{m \to 1}^{6} wv_{AF\_m(j)} \quad \text{(Eq. 4)}$$

$\eta_{(j)}$ is computed at the starting year of the simulation and is assumed as constant over time. Then, for each j-stand, $RA_{n(j)}$ is calculated as:

$$RA_{n(j)} = RP_{n(j)} \cdot \eta_{(j)} \quad \text{(Eq. 5)}$$

The annual cumulative recovery rate (η_n; -) is quantified as the ratio between the sum of the potentially available residues of all the stands (RA_n; $t \cdot yr^{-1}$ DM) and the sum of the producible residues of all the stands (RP_n; $t \cdot yr^{-1}$ DM):

$$\eta_n = \frac{RA_n}{RP_n} \quad \text{(Eq. 6)}$$

5.5.3 Wood energy equivalent and potentially generated energy

Under the assumption that RA_n ($t \cdot yr^{-1}$ DM) is transformed into woodchips, WOCAS v2 calculates the annual cumulative energy equivalent (EQ_n; $GJ \cdot yr^{-1}$; $t_{oe} \cdot yr^{-1}$) related to this biofuel by considering a range in the lower heating value of the wood (LHV_{min} and LHV_{max}, respectively; $GJ \cdot t^{-1}$ DM) and a conversion factor $k_5 = 41.86$ $GJ \cdot t_{oe}^{-1}$:

$$EQ_{n_{min;max}} = RA_n \cdot LHV_{min;max} \quad \text{(Eq. 7)}$$

$$EQ_{n_{min;max}} = (RA_n \cdot LHV_{min;max})/k_5 \quad \text{(Eq. 8)}$$

The annual potentially generated heat and electricity (TE_n and EE_n, respectively; $GJ \cdot yr^{-1}$) are respectively calculated as:

$$TE_{n_{min;max}} = RA_n \cdot LHV_{min;max} \cdot \eta_{T1} \cdot \eta_{T2} \quad \text{(Eq. 9)}$$

$$EE_{n_{min;max}} = RA_n \cdot LHV_{min;max} \cdot \eta_{T1} \cdot \eta_{E} \quad \text{(Eq. 10)}$$

where:

η_{T1} = average thermal efficiency of the thermal oil woodchip burners (-);

η_{T2} = average thermal efficiency of the ORC unit (-);

η_{E} = average electric efficiency of the ORC unit (-).

5.2.4 Potentially avoided CO_2 emissions into the atmosphere

The potentially avoided CO_2 emissions related to heat and electricity replacement (EM'_n, EM''_n, respectively; $t \cdot yr^{-1}$ CO_2) are quantified as:

$$EM'_{n_{min;max}} = V_{F\_n_{min;max}} \cdot k_6 = [TE_{n_{min;max}}/(LHV_F \cdot \eta_{T3})] \cdot k_6 \quad \text{(Eq. 11)}$$

$$EM''_{n_{min;max}} = EE_{n_{min;max}} \cdot k_7 \quad \text{(Eq. 12)}$$

where:

$V_{F\_n_{min;max}}$ = minimum and maximum volume of the substituted fossil fuel ($m^3 \cdot yr^{-1}$);

LHV_F = lower heating value of the fossil fuel ($GJ \cdot m^{-3}$);

η_{T3} = average thermal efficiency of the fossil fuel-based burners (-);

k_6 = emission factor (mass of emitted CO_2 per unit of fossil fuel volume; $t \cdot m^{-3}$ CO_2);

k_7 = emission factor (mass of emitted CO_2 per unit of generated electricity; $t \cdot GJ^{-1}$ CO_2).

Finally, the total potentially avoided CO_2 emissions are computed as:

$$EM_{n_{min;max}} = EM'_{n_{min;max}} + EM''_{n_{min;max}} \quad \text{(Eq. 13)}$$

5.3 Case Study

Valle Camonica (Figure 1) is one of the biggest valleys of the Rhaetian Alps characterized by heterogeneous ecosystems and landscape, with elevations ranging from the 390 m of the valley floor to the 3539 m of the Monte Adamello peak. The valley is characterized by a total area equal to A_T = $1.27 \cdot 10^5$ ha (12% of the mountainous area of the Lombardy Region), and includes 41 municipalities of the District of Brescia. The eastern side of the valley is covered by the Adamello Regional Park, which encompass more than 60% of the total area of the valley and includes 19 municipalities of the District of Brescia (Gerosa et al., 2013).

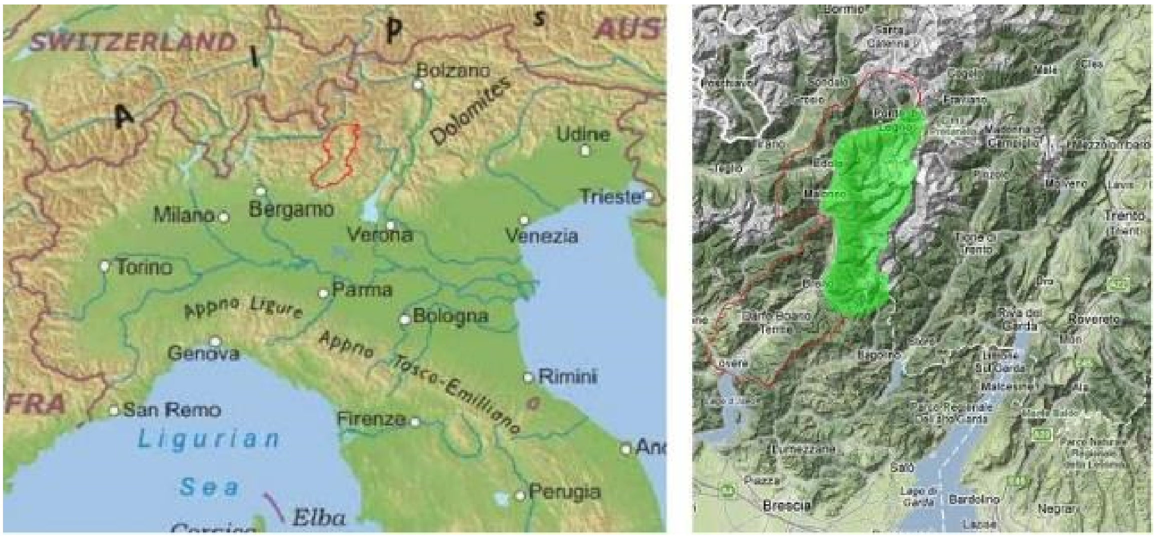

Figure 1. Localization of the Case Study Area in the Lombardy Region (left side) and localization of the Adamello Park (green area) within Valle Camonica (red burdens) (right side) (Source: Gerosa et al., 2013).

Forests are evenly distributed throughout the whole valley; the total forest area is $A_F = 6.58 \cdot 10^4$ ha; public (managed through FMPs) and private (not managed through FMPs) forests cover 64.1% and 35.9% of A_F, respectively.

Coniferous are mainly represented by: (i) *Picea abies* L. (30%) and (ii) *Larix decidua* Mill. (20%), whereas broadleaves are mainly represented by: (i) rupicolous species characterized by high physiognomic-structural disorders and occasional management (13.5%), (ii) *Alnus alnobetula* (Ehrh.) K. Koch (11%), (iii) *Castanea sativa* Mill. (8%) and (iv) formation of *Fraxinus ornus* L., *Ostrya carpinifolia* Scop. and *Quercus pubescens* Willd (5%).

For both coniferous and broadleaves high forests, $MV_{Hn(j)}$ refers to the volume of the stem over bark from the stump (30 cm above the forest floor) up to a top diameter of 7 cm of trees with a diameter at breast height higher than 17.5 cm, excluding branches and foliage. $MV_{Hn(j)}$ of coppices is generally estimated by measuring the volume of the trailer used for wood transport.

According to a recent estimation of the Mountain Community carried out in the year 2016, the total merchantable stem volume of the public forests is $6.2 \cdot 10^6$ m^3, approximately, and the total gross annual increment reaches $1.2 \cdot 10^5$ $m^3 \cdot yr^{-1}$. For high forests, the annual prescribed (planned through the FMPs) cutting volume is $4.5 \cdot 10^5$ $m^3 \cdot yr^{-1}$, whereas the extracted volume is equal to $2.3 \cdot 10^5$ $m^3 \cdot yr^{-1}$ (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 logging companies that carry out all the operations of wood felling, extraction to the landing and transport to the final user.

The merchantable stem is mainly delivered to the nineteen local sawmills, which annually process a total volume of $4 \cdot 10^4$ m^3, approximately; wood comes from both local and non-local forests (12.5% and 87.5%, respectively), and is mainly used for packaging and pellet (66%), beams (24%) and planks (10%).

Up to now, logging residues are prepared into woodchips to feed the local centralized heating plant of Ponte di Legno. This plant is made up of three different units: (i) district heating, (ii) cogeneration, consisting in an ORC system for combined heat and electricity production, and (iii) back-up unit (Table 5).

Table 5. Technical characteristics of the centralized heating plant of Ponte di Legno. Heat and electricity are produced by using woodchips deriving from both regional and non-regional forests (40% and 60%, respectively) (Source: interview to the head of the technical office].

Technical characteristics	Description
District heating unit (starting year of activity: 2009)	
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	$8.63 \cdot 10^3$ t ($4.92 \cdot 10^3$ t DM); 7966 h
Cogeneration energy unit (ORC) (starting year of activity: 2017)	
Woodchips burners (heat transfer fluid: thermal oil)	1
Burner nominal thermal power; Average thermal efficiency (η_{T1})	4.04 MW; 0.75
ORC nominal thermal power; Average thermal efficiency (η_{T2})	2.95 MW; 0.73
ORC nominal electric power; Average electric efficiency (η_E)	0.73 MW; 0.18
Year 2019: woodchips consumption; Operating time	$1.34 \cdot 10^4$ t ($7.65 \cdot 10^3$ t DM); 8121 h
Thermal back-up unit (starting year of activity: 2009)	
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

For each j-stand, data on: (i) forest structure, (ii) forest function, (iii) forest typology and variants, (iv) area (ha) and (v) harvested merchantable stem volume for each year in which cuts occurred ($MV_{Hn(j)}$; $m^3 \cdot yr^{-1}$) were extracted from the "Cadastral FMPs database" (CPA v2), made available by the Mountain Community, by considering the period between 2009 (no data on forest roads' transitability were made available for the previous years) and 2016 (more recent available data from the CPA v2); for each j-stand, all types of wood cuts were considered.

The stand's accessibility and the forest roads' transitability were not made available from the CPA v2, and therefore they were computed according to the topographic features, the landscape morphology, and the characteristics of the forest roads; to do this, the FMPs data coming from WOCAS v2 were combined with a Digital Elevation Model (DEM) in GIS software. For each polygon, latitude and longitude, boundaries and area to derive the topographic features (elevation and slope) were made available as Shapefile ESRI from the webGIS Geoportal (https://www.sportellotelematico.cmvallecamonica.bs.it/page%3As_italia%3Ageoportale). For the

GIS analysis, each stand listed in WOCAS v2 and in the attributes table of the Shapefile was marked with a unique code. This operation was necessary since it allowed to relate data of stands coming from different sources through a common field acting as a key. Then, through the function "join" available in the attribute table of the Shapefile, each stand listed in WOCAS v2 with its data on structure, function, forest typology and variants, area, and producible logging residues, was joined with the corresponding stand listed in the table of attributes characterized by the same unique code. The GIS analysis showed that:

- for 55 stands out of 2019 extracted from the CPA v2 and listed in WOCAS v2, the join was not performed, since no data on their latitude and longitude, boundaries and area were made available from the Shapefile;

- 1836 stands were characterized by a single contiguous area (single stand), and therefore it was easy to define the centroids and the topographic features; 124 stands were made up of different non-contiguous area (sub-stands), corresponding to different sub-polygons (from 2 to 14 sub-polygons, on average 3 sub-polygons per stands); in these cases, the total mass of $RP_{n(j)}$ calculated by WOCAS v2 for the whole stand was subdivided among each sub-polygon, proportionally to the area.

- Sub-polygons smaller than 1000 m^2 ($n = 49$) were excluded from the analysis. Overall, 2157 polygons – consisting of both single stands and sub-stands – were analyzed. This procedure allowed for a better consideration of environmental and infrastructure parameters, which can vary considerably at the local scale.

The map of the regional road system in the vector format and forest roads data (year of update: 2019) were obtained from the Lombardy Region Geoportal (http://www.geoportale.regione.lombardia.it/). The DEM was made available by the Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM) (https://www2.jpl.nasa.gov/srtm/). Data used here referred to the year 2014 and are characterized by a spatial resolution of 1-arcsec (30m). The slope was calculated by using the software SAGA GIS (Schillaci et al., 2015). The average slope was assumed as constant for the whole polygon. This may represent a quite strong assumption, especially for stands with a high area, since slope can vary considerably. Moreover, not having specific information on the exact place inside the polygon where the wood cut was performed, also the distance from the nearest forest road was calculated from the centroid. Figure 2 summarizes the steps of the calculations.

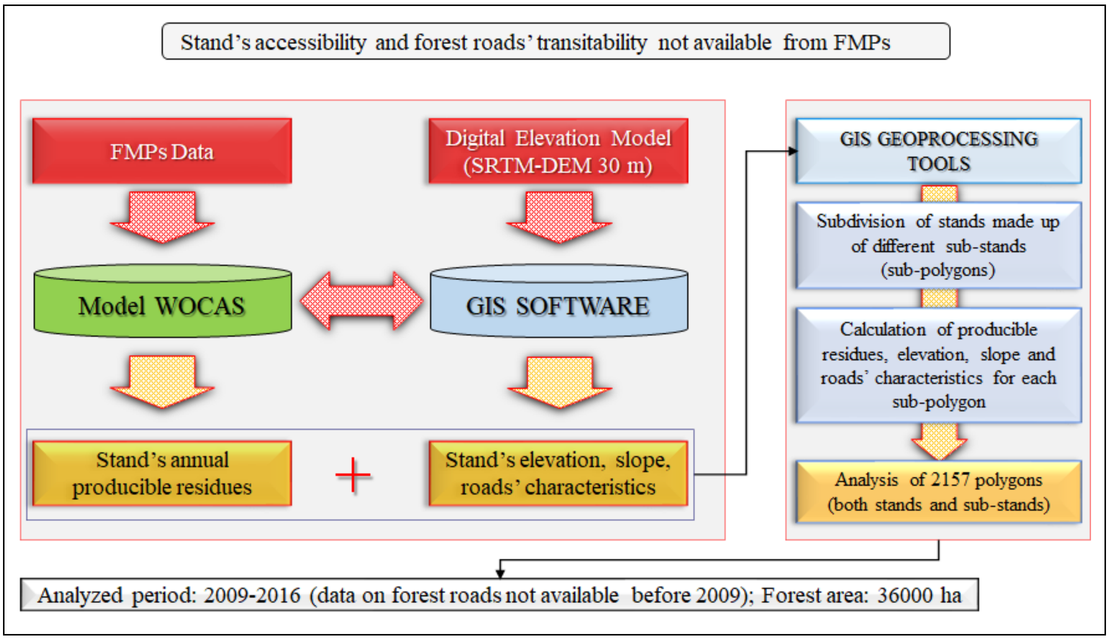

Figure 2. Schematization of the step followed for the calculation of the potentially available logging residues.

Table 6 and Table 7 show the number of polygons and the average area (with the corresponding standard deviation) for each accessibility and transitability class, respectively.

Table 6. Number of polygons, average area, and corresponding standard deviation for each accessibility class.

Accessibility Class	Polygons	
	Number	Average area ± s.d. (*)
	(-)	(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

(*) Standard deviation.

Table 7. Number of polygons, average area, and corresponding standard deviation for each transitability class.

Transitability Class	Polygons	
	Number	Average area ± s.d. (*)
	(-)	(ha)
Medium-low (TC III + IV)	1376 (64%)	15.24 ± 10.38
Medium-high (TC I + II)	781 (36%)	19.26 ± 20.22

(*) Standard deviation.

Figure 3 shows the distribution of the polygons along the whole District, according to the main function.

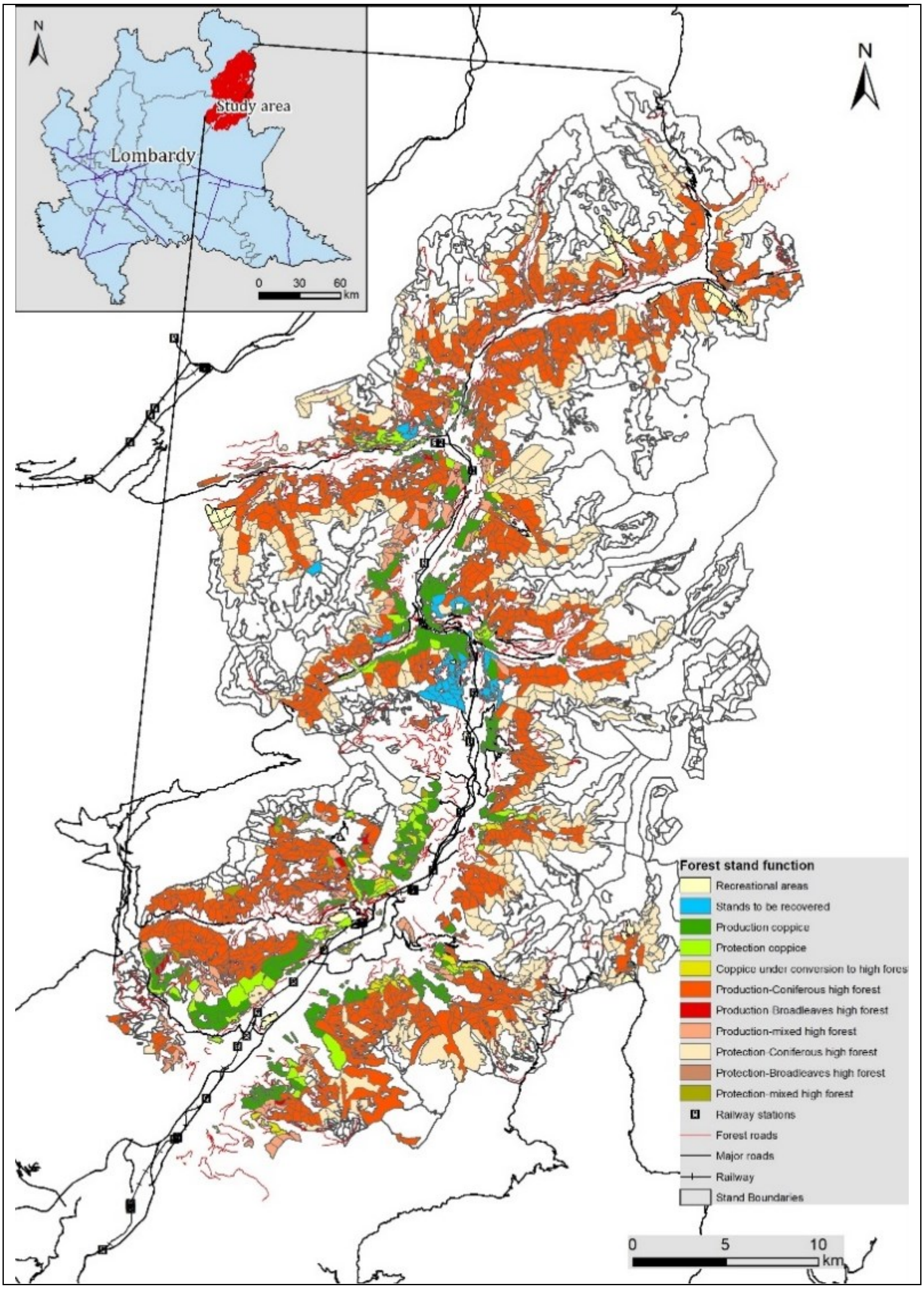

Figure 3. Distribution of the polygons according to the main function.

Figure 4 shows the distribution of the polygons according to the average slope.

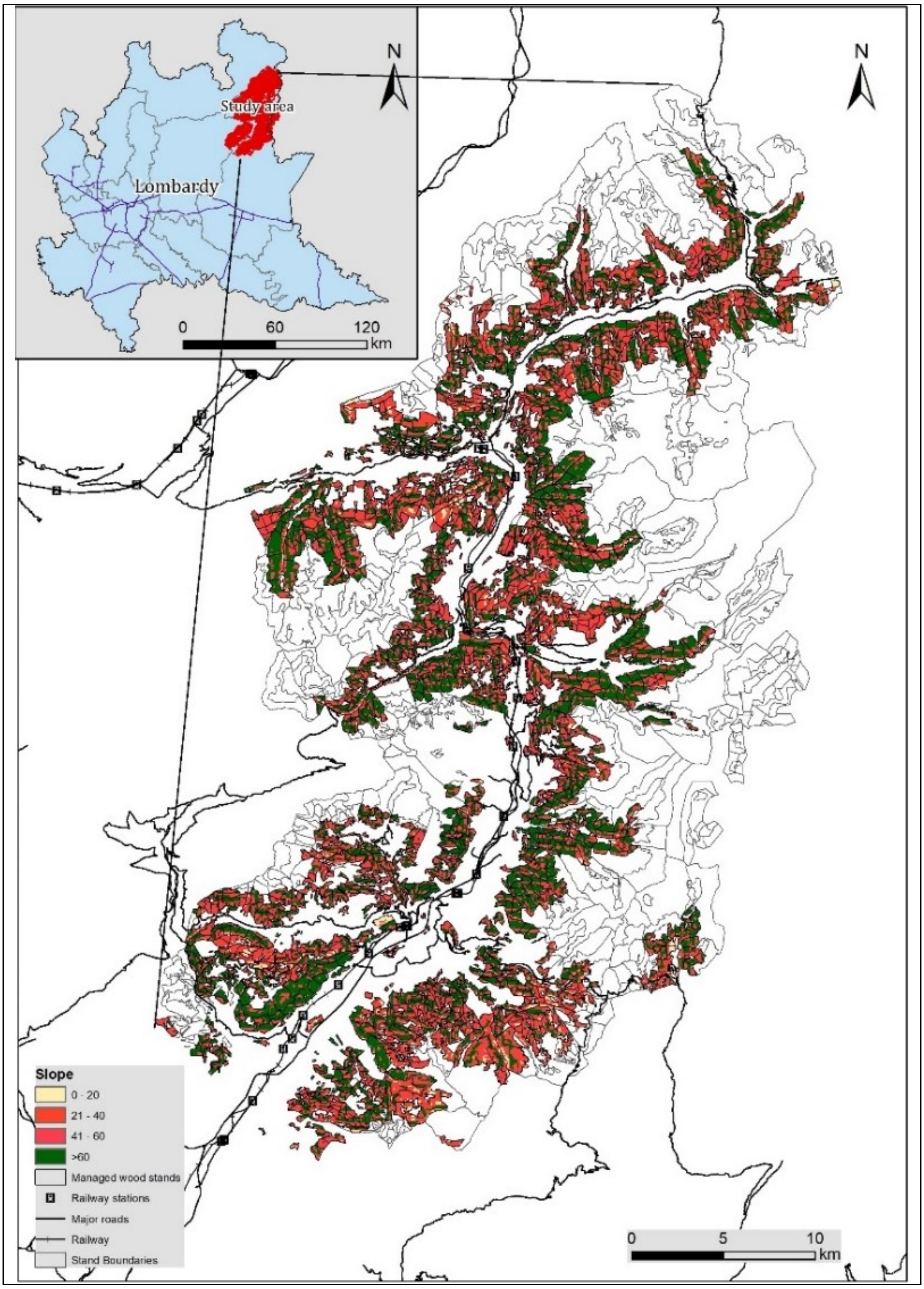

Figure 4. Distribution of the polygons according to the average slope.

Figure 5 shows the distribution of the forest roads according to the transitability classes.

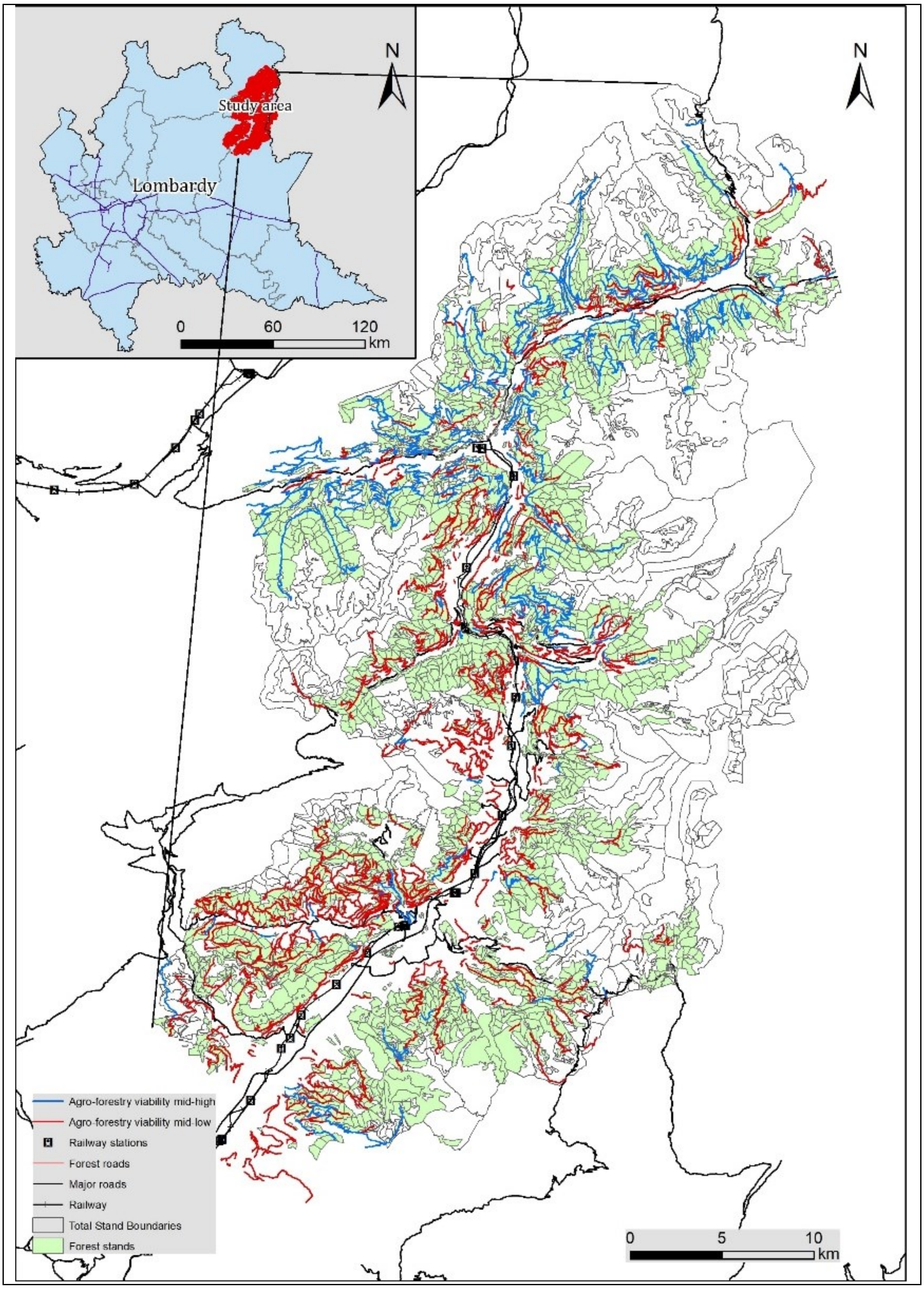

Figure 5. Distribution forest roads according to the transitability classes.

To calculate the producible residues, different values of k_1 and k_2 were used for each classification criteria code, starting from the ones reported in Federici et al. (2008) for Italian forest species and applied at the regional level for biomass and C accounting for the UNFCCC.
The availability factor 3 (harvesting method) was not considered since specific information at the stand level was not available. For the availability factor 5 (energy market demand), a maximum value was associated to stands with production function, whereas a low value was associated to all the other stands. The same weight ($w_{AF\_1(j)} = w_{AF\_2(j)} = w_{AF\_4(j)} = w_{AF\_5(j)} = w_{AF\_6(j)} = 0.20$) was assigned to the availability factors.
The wood energy equivalent and the potentially generated heat and electricity were quantified by assuming an average value of LHV_{min} and LHV_{max} equal to 17.5 $GJ \cdot t^{-1}$ DM and 20.5 $GJ \cdot t^{-1}$ DM, respectively (Fiala, 2012). For η_{T1}, η_{T2} and η_E, the same values of that reported in Table 5 were assumed. The potentially avoided CO_2 emissions related to the combustion process were calculated under the hypothesis that:

- heat generated by the ORC unit replaced the one produced by conventional plants feed with natural gas, which represents the most used fossil fuel for heat generation in Valle Camonica;

- electricity generated by the ORC unit replaced the one produced by the Italian natural gas-based plants-mix for combined heat and electricity production and distributed through the National grid.

The following values were adopted: (i) $LHV_F = 3.53 \cdot 10^{-2}$ $GJ \cdot m^{-3}$ (standard conditions); (ii) $k_6 = 1.97 \cdot 10^{-3}$ $t \cdot m^{-3}$ CO_2 (Italian Ministry for the Environment, 2018) and (iii) $k_7 = 9.81 \cdot 10^{-2}$ $t \cdot GJ^{-1}$ CO_2 (National Environmental Information System, 2018).

5.4 Results and discussion

5.4.1 Producible and potentially available logging residues

For the whole analyzed period (2009-2016), the total mass of RP, calculated as the sum of the annual mass of RP for each polygon, was $RP_{tot} = 2.46 \cdot 10^4$ t DM. By including the availability factor n. 4 (stand's accessibility) and n. 5 (forest roads' transitability) the total mass of potentially available residues for the whole analyzed period, computed as the sum of the annual mass of available residues in each polygon, was $RA_{tot} = 1.35 \cdot 10^4$ t DM. On the contrary, if the stand's accessibility and forest roads' transitability were not considered, the total mass of potentially available residues for the whole analyzed period amounted to $RA'_{tot} = 1.65 \cdot 10^4$ t DM. In other words, the exclusion of accessibility and transitability from the calculations caused – for the whole period – an overestimation of the potentially available residues equal to 21.4%. Figure 6 shows RA and RA' for each year of the analysis.

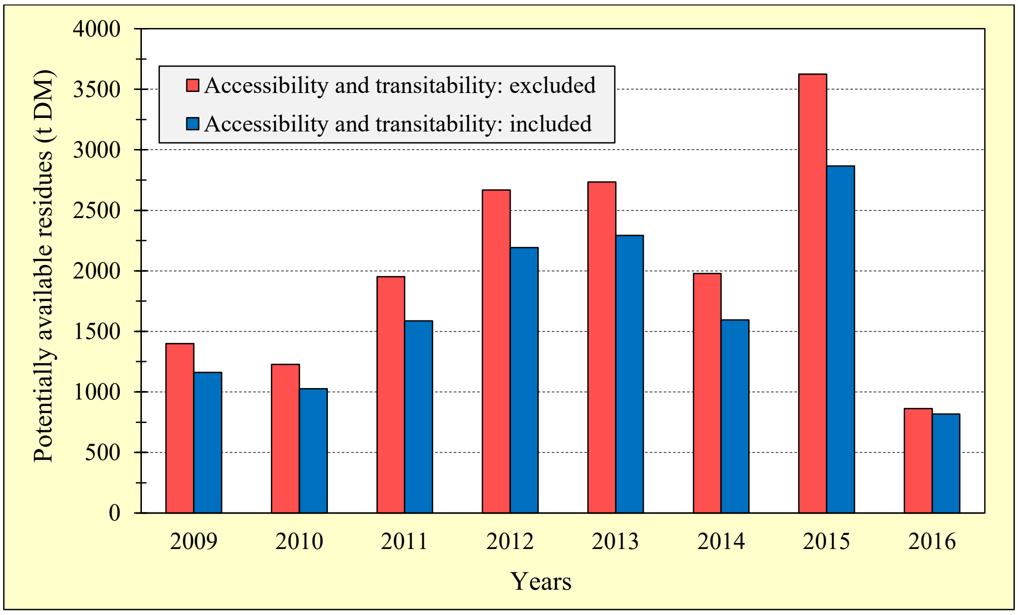

Figure 6. Potentially available logging residues calculated both including and excluding stand's accessibility and forest roads' transitability (blue bars and red bars, respectively). In both cases, the harvesting method is excluded. For each year, the total value is the sum of the values related to each polygon.

The following general consideration can be made:

- from 2009 to 2015, the mass of RA and RA' increased each year, except for 2010 and 2014, in which the mass of potentially available logging residues was lower compared to 2009 and 2013, respectively;

- the highest mass of RA and RA' occurred in 2015 ($2.87 \cdot 10^3$ t DM and $3.62 \cdot 10^3$ t DM for RA and RA', respectively) and this was mainly due to improvements in: (i) management of logging companies and (ii) forestry mechanization;

- the highest overestimation occurred in 2015 (+26.4%), whereas the minimum in 2016 (+5.6%). This great difference along the analyzed period was caused by the fact that, year by year, new stands with different characteristics of accessibility and transitability can be included in the analysis.

- the year 2016 was characterized by a strong reduction of RA and RA' compared to the previous year, probably due to the lack of data in the CPA v2;

It should be underlined that, for all the analyzed polygons, the potentially available logging residues included also the mass used by residents for personal use. This mass should be deducted from the total to avoid overestimations of the mass available for energy generation. For this study, the mass used by residents was not made available by the CPA v2 and, therefore, it was included in the calculation.

Another aspect that need to be discussed concerns the use of the parameter k_2 (i.e., biomass expansion factor). Biomass expansion factors represent a very critical component for biomass estimation. Sharp et al. (1972) firstly used constant values of biomass expansion factors to quantify the forest biomass at the regional level, in North Carolina (USA), starting from forest inventory data. Constant values of biomass expansion factors were also used later for other broad-scale forest biomass estimations in the tropical (Brown and Lugo, 1984), and in the European forests (Kauppi et al., 1992). Future studies demonstrated that the biomass expansion factors are not constant, but vary according to stand's species, age, productivity, environmental conditions, management, and volume (Nilsson et al., 2000; Fang and Wang, 2001; Levy et al., 2004; Wirth et al., 2004). Using constant values of biomass expansion factors can cause an underestimation of the biomass for younger and less productive stands, and an overestimation for older and more productive ones (Goodale et al., 2002). Fang et al. (2005) and Fang and Wang (2001) proposed a method through which the biomass expansion factor can be computed according to the stem volume by using a reciprocal equation. Other methods based on the stem volume for biomass expansion factor calculation were proposed by Brown et al. (1999) and Brown and Schroeder (1999). Lehtonen et al. (2004) proposed a method for the quantification of biomass expansion factors based on stand's age.

Stem volume itself incorporates the effects of age, productivity, as well as other biotic and abiotic factors and, therefore, it can be directly used as independent variable to estimate the biomass expansion factors and the biomass, without the need to collect other information. Using stem volume-dependent biomass expansion factors generally increases the accuracy of biomass estimation compared to the use of age-dependent factors (Fang et al., 2002; Teobaldelli et al., 2009; Guo et al., 2010).

Considering all these elements, and since the volume of the stands is always reported in the FMPs, the function of stem volume-dependent biomass expansion factors proposed by Teobaldelli et al. (2009) was implemented into WOCAS v2 to improve the flexibility of the model. This would also allow a user to perform a sensitivity analysis to investigate how the biomass estimation can vary

depending on whether variable or constant biomass expansion factors are used. The use of other functions to calculate the biomass expansion factors, e.g., those based on stand's age, is not always applicable, since the age is not always made available from FMPs.
Despite this, it is crucial to make some clarifications to explain why, in the present study, constant values of biomass expansion factors were used for each stand, according to its classification criteria code. First of all, the method proposed by Teobaldelli et al. (2009) is characterized by an important approximation, since it assumes that low stand volume (or mass) corresponds to low age, and vice versa. Stands characterized by the same volume may have different ages, according to the environmental conditions, history, and management practices. Again, under particular situations, stands can have low age but high volume, or vice versa; therefore, the volume-age linearity is not always verified. Therefore, the method of Teobaldelli et al. (2009) should be used only if the real characteristics of the stand are known.
Finally, as also pointed out by the authors, the parameters of the non-linear regression function were estimated starting from data related to large geographical areas from all over the world characterized by different ecological and management conditions, and thus inherently involving large variations. Therefore, biomass expansion factors estimated through this method should not replace local data, which should be always preferred if available. Because of this – even if constant – the values of biomass expansion factors reported in Federici et al. (2008) for Italian forests species – also applied at the regional level for biomass and C stock accounting within the UNFCCC – were adopted.
Specific values of biomass expansion factors for the Italian Alps were recently developed also by Zambelli et al. (2012) starting from data on residues production collected by Spinelli and Magagnotti (2007) and data coming from the tariff tables produced by Castellani et al. (1984) and Pedrolli (1999), but they referred to coniferous species only; moreover, data reported by Spinelli and Magagnotti (2007) referred to working conditions of Eastern Italy, where specific wood cuts and harvesting technologies were applied. Because of this, the values of biomass expansion factors of Zambelli et al. (2012) were not considered in this work.

5.4.2 Recovery rate of producible logging residues

For the whole analyzed period, the average recovery rate, calculated as the ratio between RA_{tot} and RP_{tot}, was η_{tot} = 55.0%, ranging from 52.5% (2010) to 59.7% (2016) (Figure 7). η_n varied over time since new stands with different characteristics were included in the analysis year-by-year.

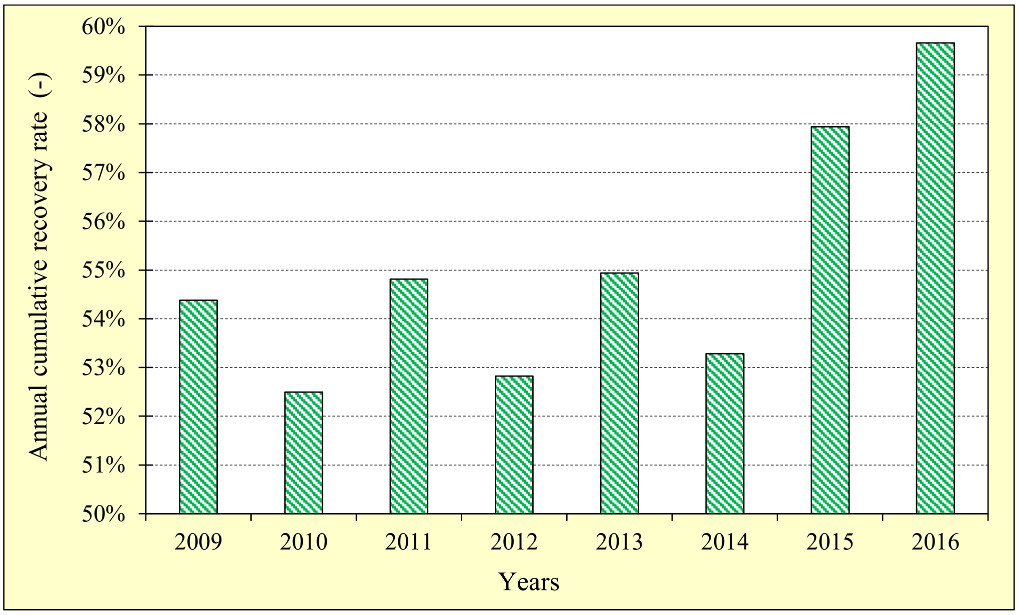

Figure 7. Recovery rate of the producible logging residues. For each year, the value was calculated as the ratio between the total potentially available residues and the total producible residues related to all the polygons.

As mentioned above, the values of recovery rate here presented resulted from empirical values associated to the different availability factors.

The recovery rate values calculated by this study can be compared to that reported by Thiffault et al. (2014); the authors analyzed 68 scientific studies and technical reports to define the recovery rate of logging residues for boreal and temperate forests characterized by very different climatic, environmental, and operating conditions, and to analyze the main factors affecting its variability. The selected studies and reports were mainly based on the following harvesting methods: (i) cut-to-length; (ii) bundling and (iii) full-tree.

Among all the analyzed studies, the average recovery rate of residues was 52.2%, with a standard error of 18.1%. The distribution of the values resulted close to a normal distribution, with 70.6% of the values within one standard deviation of the mean. The minimum value of the recovery rate was 4.0%, whereas the maximum amounted to 89.1%.

The authors found that the most important factor driving the recovery rate of residues was the country in which wood collection took place. Northern EU countries, like Finland and Sweden, showed the highest recovery rate, i.e., 71.6%, approximately. This was mainly due to the introduction of strong bioenergy policies and measures after the oil crisis in 1970s to promote the use of wood biomass for energy purposes. This, in turn, increased the economic value of the residues (and therefore the incentive for their removal), followed by technological innovation for the reduction of the production costs along the whole supply chain (Junginger et al., 2005; Thiffault et al., 2014).

Another important aspect affecting the high recovery rate in Northern EU countries was the characteristic of the forest, i.e., softwood plantation in which the uniformity of tree species, size, and space facilitates all the mechanized operations.

On the contrary, in non-Nordic countries – where energy policies for residues use were not so strong – the main factors affecting the recovery rate were the harvesting methods and the season; for the cut-to-length method, Thiffault et al. (2014) reported an average recovery rate of 35.6%, approximately, whereas, for the full-tree and the bundling method, the average rate amounted to 48.1% for operations performed in summer and 60.7% for operations performed in autumn, winter, and spring. This was generally due to the fact that collecting residues on a snowy surface is easier compared to a heterogeneous surface. Moreover, in autumn, winter and spring, residues are generally characterized by a higher moisture content than in summer, and therefore are less prone to breakage (Thiffault et al.; 2014).

None of the analyzed studies defined the minimum mass of residues which should be left in the forest for ecological-environmental functions.

In Italy, Spinelli et al. (2016) investigated *Picea abies* L. and hardwoods species in cable yarding where the residues recovery rate after applying the full-tree method ranged from 10 to 70%, i.e., from 30 to 90% of residues are left on site. In French forests, Cuchet et al. (2004) found that the recovery rate of residues when applying the cut-to-length method was equal to 50%.

It should be noted that even in Italy, at the national and regional level, there are still no specific regulations and policies for the definition of thresholds concerning the maximum amount of wood removal to ensure the sustainability of forest ecosystems.

For this study, under the hypothesis that in the years 2009-2015 forests were sustainably managed – and had a specific structure and mean tree volume – the current harvested mass of residues can be reasonably assumed as constant and equal to the average value quantified for that period, i.e., $1.82 \cdot 10^3 \pm 6.61 \cdot 10^2$ $t \cdot yr^{-1}$ DM. This assumption can be acceptable only if silvicultural treatments, total volume, and average productivity of the forests are similar among the years, and therefore it is valid only for a limited period of time.

Estimation for the long term is uncertain since it is affected by: (i) climate change (increase of trees' stress conditions); (ii) increase of the probability of disturbances and extreme events in general (trees will become more susceptible to both biotic and abiotic factors) and (iii) variability of the wood market price.

As mentioned before, the availability factor n. 3 (harvesting method) was not considered in the calculation, since no data were made available at the stand level. Adopting a harvesting method rather than another, as well as specific machines and technologies, considerably affects the available mass of residues (Zambelli et al., 2012). Future research is needed to consider all these elements and calculate a recovery rate by considering all the availability factors.

Experimental tests are also needed to collect information on the currently harvested mass of residues to perform the validation of the results, which up now is not possible since no measured data are available at the stand level.

5.4.3 Energy equivalent, potentially generated energy and avoided CO_2 emissions

The EQ related to the estimated currently harvested mass ($1.82 \cdot 10^3 \pm 6.61 \cdot 10^2$ $t \cdot yr^{-1}$ DM) was $3.18 \cdot 10^4 \div 3.72 \cdot 10^4$ $GJ \cdot yr^{-1}$ (equal to $7.59 \cdot 10^2 \div 8.89 \cdot 10^2$ $t_{oe} \cdot yr^{-1}$). Considering only the ORC unit of the Ponte di Legno plant, the potentially generated heat and electricity, the potentially avoided natural gas consumption and CO_2 emissions into the atmosphere related to the use of the local logging residues are shown in Table 8.

If only the current harvested mass of residues was used to feed the ORC unit of the plant, the potentially generated heat and electricity would represent at most 28.7% of that generated by the unit in the year 2019. The thermal and electric power would be, at most, equal to 0.70 MW and 0.17 MW, with an average power load of the ORC unit of 23.6%.

Table 8. Potentially generated energy, potentially avoided natural gas consumption and potentially avoided CO_2 emissions into the atmosphere related to the use of local woodchips in the ORC unit of the Ponte di Legno plant.

Type of energy	Potentially generated energy	Potentially avoided natural gas consumption	Potentially avoided CO_2 emissions into atmosphere
	($GJ \cdot yr^{-1}$)	**($m^3 \cdot yr^{-1}$) (std. conditions)**	**($t \cdot yr^{-1}$ CO_2)**
Heat	$1.74 \cdot 10^4 \div 2.04 \cdot 10^4$	$5.80 \cdot 10^5 \div 6.79 \cdot 10^5$ [a]	$1.14 \cdot 10^3 \div 1.34 \cdot 10^3$ [c]
Electricity	$4.30 \cdot 10^3 \div 5.03 \cdot 10^3$	$2.08 \cdot 10^5 \div 2.43 \cdot 10^5$ [b]	$4.22 \cdot 10^2 \div 4.94 \cdot 10^2$ [d]
Total	-	$7.88 \cdot 10^5 \div 9.22 \cdot 10^5$	$1.57 \cdot 10^3 \div 1.83 \cdot 10^3$

Notes: [a] average thermal efficiency of the household burners feed with natural gas: 0.85; [b] average specific consumption of plants-mix for heat and electricity production feed with natural gas: 6143 $kJ \cdot kWh^{-1}$ of gross electricity (Source: TERNA, 2018); [c] average emission factor for natural gas: $1.972 \cdot 10^{-3}$ $t \cdot m^{-3}$ CO_2 (Source: Italian Ministry for the Environment, 2018); [d] average emission factor of plants-mix for heat and electricity production feed with natural gas: $9.81 \cdot 10^{-2}$ $t \cdot GJ^{-1}$ CO_2 (gross electricity) (Source: National Environmental Information System, 2018).

The annual energy equivalent is calculated starting from the potentially available residues at the landscape level and assuming a range in the lower heating value of wood. The methodology can be improved by computing the energy equivalent for each stand/polygon by using a lower heating value for each forest typology.

Moreover, it is necessary to point out again that the potentially avoided CO_2 emissions into the atmosphere were computed only for the final combustion process.

The CO_2 balance of a bioenergy system depends on the type of feedstock sources, conversion technologies, end-use technologies, system boundaries, and reference energy system with which the bioenergy chain is compared (Cherubini et al., 2009). Energy from wood is considered to be "carbon neutral" over its life cycle, since the combustion of biomass releases into the atmosphere the CO_2 that was previously sequestered by trees during growth; on the contrary, fossil fuels release CO_2 that has been locked up for millions of years (IPCC, 2000; Cherubini et al., 2009). This is true for the long-term, but in the short-term, CO_2 and other GHGs are emitted from the different phases of the supply chain, since fossil fuels are required for wood production and harvesting, processing, storage, handling, and transport to the final user (Cherubini et al., 2009; Routa et al., 2011).

Searchinger et al. (2008) and Melillo et al. (2009) questioned the concept of "carbon neutrality" of wood, due to the high indirect GHGs emissions in different phases of the supply chain. In Finland, Routa et al. (2011) estimated the CO_2 emissions (kg $CO_2 \cdot MWh^{-1}$ of generated energy) for integrated production of timber and logging residues for energy in stands of *Picea abies* L. and *Pinus sylvestris* L. under different productivity levels and silvicultural treatments over a period of 80 years, by considering all the operations needed to growth, harvest and transport the biomass to an energy plant. The authors found that differences exist between species and sites but, in general, the fossil fuel energy consumption varied between 2.2% and 2.8% of the total energy generated by using wood. In conclusion, the authors pointed out that the primary energy use and CO_2 emissions related to the whole forest-wood-energy chain were lower compared to the increased potential of energy biomass.

5.5 Conclusion

The increase in energy demand and the low energy self-sufficiency of our Country leads to a growing interest in using bioenergy, and in particular logging residues, to promote the transition into local low-carbon emission economies. It is therefore necessary to plan "sustainable energy districts" based on the real availability of wood, by taking into account also the environmental protection and the needs of the local populations.

This paper presented the methodology implemented into the model WOCAS v2 to estimate the mass of the potentially available logging residues in an Alpine area, at the stand level, from the year in which the FMPs entry into force until a predefined reference year. All the data used for the analysis can be easily collected, and therefore the methodology can be applied also in other areas.

The stand's accessibility and the forest roads' transitability were computed by taking into account to the topographic features, the landscape morphology, and the characteristics of the forest roads. To do this, the FMPs data coming from WOCAS v2 were combined with a DEM in GIS software.

Despite the presented methodology is focused only on the quantification of branches and tops, it should be underlined that an additional biomass supply for energy purposes could also come from non-merchantable stems of thinning of high forests – mainly performed to enhance the growth rate or the health of the remaining trees – and, in general, from silvicultural treatments where the stems have poor physical-structural characteristics (e.g., due to phytopathological agents) to be used for building purposes and long life-cycle products in general.

The past potentially available residues were estimated for the Valle Camonica District for the period 2009-2016. According to the annual values calculated for the period 2009-2015, the current sustainable supply was calculated. Then, assuming that this mass was used as woodchips to feed the ORC unit of a local centralized heating plant, the potentially generated heat and electricity and the potentially avoided CO_2 emissions into the atmosphere were quantified by assuming that the local woodchips substituted non-renewable energy sources.

Even if the methodology is based on six availability factors, the harvesting method was not considered for the Case Study, since no information was made available at the stand level. Therefore, further research is needed to collect information about the harvesting method as well as the used machines and technologies. Experimental tests must be carried out also to collect data on the currently harvested mass of residues for the validation of the results, that up now is not possible since no measured (primary) data are available at the stand level.

Generally speaking, a future perspective concerns the quantification of the future residues availability for the medium-long term, by considering also economic parameters, such as the cost of logging residues extraction according to the forestry and the operating conditions, and the selling price. For this purpose, participatory processes involving public decision makers, local forestry authorities, and supply chain operators could be useful to define priority management interventions.

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Chapter 6 – Selecting and calculating economic costs of forestry machinery chains according to the forestry and operating conditions: an innovative approach

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Abstract: Selecting the most suitable machines for forestry operations (FO) is crucial to evaluate the economic costs of the whole forestry machinery chain (FMC). This evaluation is essential to support local forestry authorities and logging companies in awarding public grants/subsidies and setting transparent FO tariffs, respectively. Nevertheless, there is still a lack of generalized approach to make this selection feasible quantifying, at the same time, the economic costs of the whole FMC. The aim of the work is to develop an innovative approach in order to: (i) select the most suitable FMC to adopt for wood collection (harvesting and transport) and (ii) calculate the economic costs (€·h^{-1}; €·t^{-1} dry matter, DM; €) of each operation that compose the FMC. To make this selection feasible, a model called "FOREstry MAchinery chain selection" (FOREMA v1) was developed. FOREMA v1 operates at the forest stand level and is made up of a database called "definition of forestry machinery chain" and a user-friendly interface. The database represents the underlying logic of the model; in it, the feasible FMCs are defined by combining the categories that compose seven technical parameters: (i) stand's management system, (ii) wood assortment, (iii) harvesting method, (iv) level of mechanization, (v) forest roads transitability, (vi) stand's accessibility and (vii) mass of the harvested wood. For each FMC, FOREMA v1 defines the sequence of operations and the types of usable machines. In the user-friendly interface the user selects the categories of each parameter and choose the types of machines to use according to the suggestions of the database. Starting from the results provided by FOREMA v1, the economic costs of each operation are computed. The total cost of an operation is given by the sum of (i) fixed costs (financial depreciation, insurance, taxes, garaging, supervision, and management) and (ii) variable costs (repair and maintenance, fuel and lubricant, and labor). The total cost of the FMC is given by the sum of the total costs of the operations. The proposed approach was applied for a Case Study concerning the collection of woodchips from a coppice stand in the Italian Alps for energy generation and results are discussed.

Keywords: decision-support models, economic costs, forestry machinery chain, forestry operations, operating conditions, wood collection.

6.1 Introduction

Wood represents one of the most important ecosystem services provided by the forests, and it can be used for energy generation (heat and/or electricity) and building purposes, contributing to mitigate climate change (Rüter et al., 2016).

Wood collection refers to cutting and delivering trees in a productive, safe, economic, and ecological way, through which standing trees are converted into merchantable assortments according to the specific industrial or individual requirements and needs (Nutto et al., 2016; Pereira Castro et al., 2016). The whole process of wood collection consists of several operations (phases): (i) felling (cutting down the trees), (ii) delimbing (cutting off branches and – in the case of coniferous – tops), (iii) debarking (removing the bark from the stems of the felled trees), (iv) sectioning (subdividing the stems of felled trees into portions of specific length according to the final use of the wood), (v) extraction (transporting the whole tree or part of it for further processing inside the forest or for further transport), (vi) piling and loading (preparing the assortment for loading on a landing zone or forest road) (Greudlich, 1996; Nutto et al., 2016; Pereira Castro et al., 2016). When branches, tops and the non-merchantable stem parts are used for energy generation, chipping is also present.

For each operation, different machines and equipment can be used, ranging from purely manual to fully mechanized ones. Machines and equipment can successfully operate under a wide range of conditions, and the conditions suitable to each machine can overlap considerably; this means that the same operation can be performed by using different types of machines. Selecting the most suitable machines to use is crucial to make wood collection more productive and efficient (Kühmaier and Stampfer, 2010) while increasing the safety of forest workers and limiting their physical stress.

In many cases, the selection of the most suitable machine is still based on the experience and intuition of forest workers and technicians, and often does not consider possible changes in the long term, e.g., harvested volume, development of new machines and technologies, as well as road network improvement (Kühmaier and Stampfer, 2010). Environmental, economic, and social factors should also be considered, such as forest's characteristics (Stampfer et al., 2003), characteristics of the roads, extraction distance and soil conditions (Kellogg and Bettinger; 1994; Stampfer and Steinmueller, 2004; Stampfer et al., 2010; Monarca et al., 2011), harvesting method and level of mechanization (Proto et al., 2017) and climate (Mokhirev, 2017).

According to Pereira Castro et al. (2016) the main parameters that, in the short term, affect the selection of the machines are: (i) costs of the fuel, (ii) training of the employees and (iii) productivity of the machines, whereas, for the long term, the main parameters are: (i) level of mechanization, (ii) logistics, (iii) forest roads conditions and (iv) required wood assortment. The authors proposed a very detailed classification of the parameters influencing machines' selection for: (i) felling, (ii) extraction and (iii) processing (debarking, delimbing, sectioning/chipping), and presented the most used combination of machines for different operations for both native and planted forests. According to FAO (2001), the main parameters affecting wood collection are: (i) tree species, (ii) forest structure, (iii) quality of the wood, (iv) individual trees' volume and (v) wood assortment.

When developing a forest-wood supply plan, it is essential to provide the stakeholders with models able to support them in defining the most suitable machines to use and quantifying the economic costs of the operations that made up the whole forestry machinery chain (FMC).

Lüthy (1998) proposed a Decision Support System (DSS) to identify the best suitable machines to use under slope conditions, and to compute the corresponding economic costs. Yoshioka and Sakai (2005) performed a Geographic Information System (GIS) analysis by taking into consideration different types of machines (i.e., sledge yarder, tower yarder and skidder) and wood biomass type (i.e., logging residues, thinned trees, and broadleaved forests) to calculate the lowest economic costs for wood collection. Kühmaier and Stampfer (2010) developed a GIS-based model to define the most suitable machine to use for different environmental conditions (climate, stand and soil characteristics) and stakeholder interests, by taking into account also different ecological, economic, and social aspects. Recently, Ackerman et al. (2014) developed the user-friendly MS Office Excel-based model "COST", that allows the quantification of the economic cost of a single operation. This model is easy to use and gives the users a simultaneous view of the input parameters and costs outputs. Nemestothy (2014) developed the Windows-based application "HeProMo", to estimates the costs for different operations and FMCs, according to the types of machines defined by the user. This model is aimed at forestry companies, loggers, forestry administrations and training institutes, as well as developers of software for forestry applications. Another example of a Windows-based application is the model ECOCOST (Lan, 2001), through which basic cost calculation methods are used for different types of forestry machines to compute the costs of wood collection. Among the web-based solution, the model WoodChainManager (Triplat et al., 2020) is one of the most used, since it allows the calculation of the costs for a wide range of machines and operations.

There are, therefore, several models currently available to support the user's decisions. In some of these models, the types of usable machines are not provided as an output, but have to be defined as an input by the user, through which the economic costs of the whole FMC are subsequently calculated, e.g., in the HeProMo. Other models (e.g., the COST model) allow the computation of the cost for a single operation and not for the whole FMC. Again, in other cases, the models suggest the most suitable types of machines but only according to few technical parameters, e.g., harvested volume or slope.

Considering all these elements, it is possible to conclude that there is still a lack of generalized approach to select the most suitable FMC and quantify, at the same time, the economic costs of each operation that compose the selected chain.
In the Italian Alps, local forests are generally managed through the Forest Management Plans. The basic management unit of each Plan is the single forest stand, i.e., an aggregation of trees over a specific area and sufficiently uniform for species composition, structure, and soil conditions to be distinguished from other aggregations of trees on other areas. For each stand, the Plan defines the silvicultural treatments to be performed over a specific period of time, in order to preserve the environmental, naturalistic, productive, and social functions.
Making available models to select the most suitable FMC at the stand level can contribute to integrate knowledge related to forest management and ecology with knowledge related to mechanization, promoting an efficient use of the local forestry resources.
Considering all these elements, the aim of this work is to develop a modelling approach operating at the forest stand level in order to: (i) select the most feasible FMC to adopt for wood collection (i.e., harvesting and transport) and (ii) calculate the economic costs (cost per unit of time, $€\cdot h^{-1}$; cost per unit of product, $€\cdot t^{-1}$ of dry matter, DM; cost of production, €) of each operation that made up the selected FMC. The approach here described was applied for a Case Study concerning the production of woodchips from a coppice stand in the Italian Alps for energy generation and results are presented. The proposed approach can be used to support local administration (e.g., forestry authorities) and supply chain operators (e.g., logging companies) to award public grants/subsidies, and to define forestry operations tariffs, respectively.

6.2 Materials and Methods

6.2.1 The model FOREstry MAchinery chain selection (FOREMA v1)

To support the selection of the most suitable FMC for a specific forest stand, the MS Office Excel-based model "FOREstry MAchinery chain selection" (FOREMA v1) was developed. This model is made up of a database called "Definition of forestry machinery chain" and a user-friendly interface (Figure 1). The database represents the supporting logic for the user-friendly interface, and it is made up of three different tables (Perrotta, 2021):

- Definition of: classification code;
- Definition of: sequence of operations;
- Definition of: types of usable machines and qualitative level.

The spreadsheet "User-friendly interface" represents the interface through which the user can select the categories for the parameters that characterize the stand and choose the types of machines to use, according to the suggestions of the database. The spreadsheet is divided into the following three tables (Perrotta, 2021):

- Selection of: category for each parameter;
- Selection of: types of usable machines;
- Selected types of usable machines.

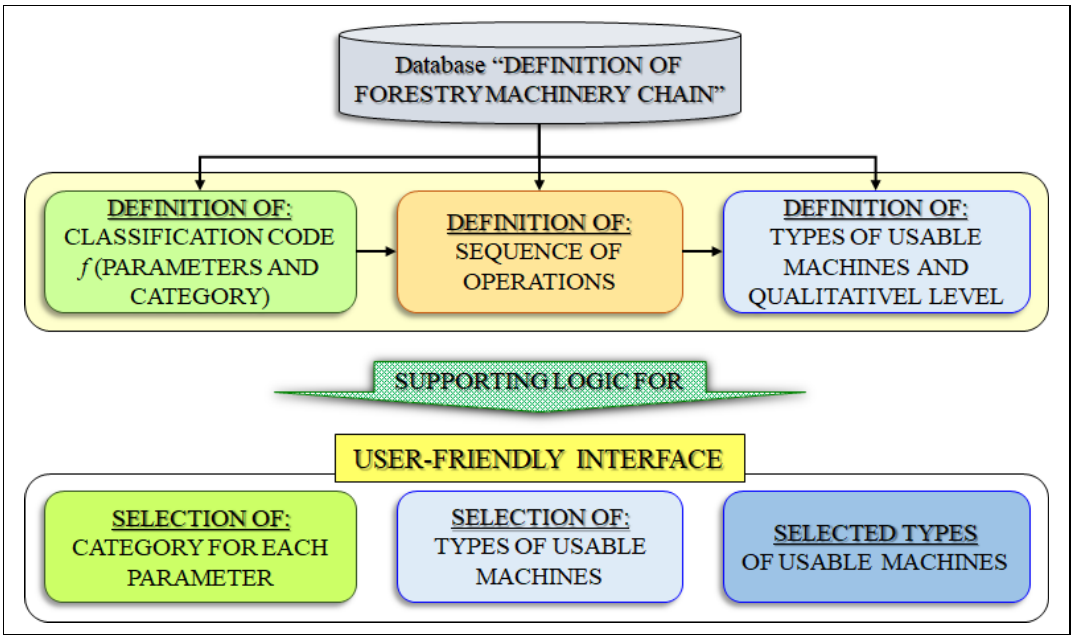


Figure 1. Logical framework of the model FOREMA v1.

6.2.1.1 Database "Definition of forestry machinery chain"

This database is made up of three tables (Figure 2):

- Definition of: classification code;
- Definition of: sequence of operations;
- Definition of: types of usable machines and qualitative level.

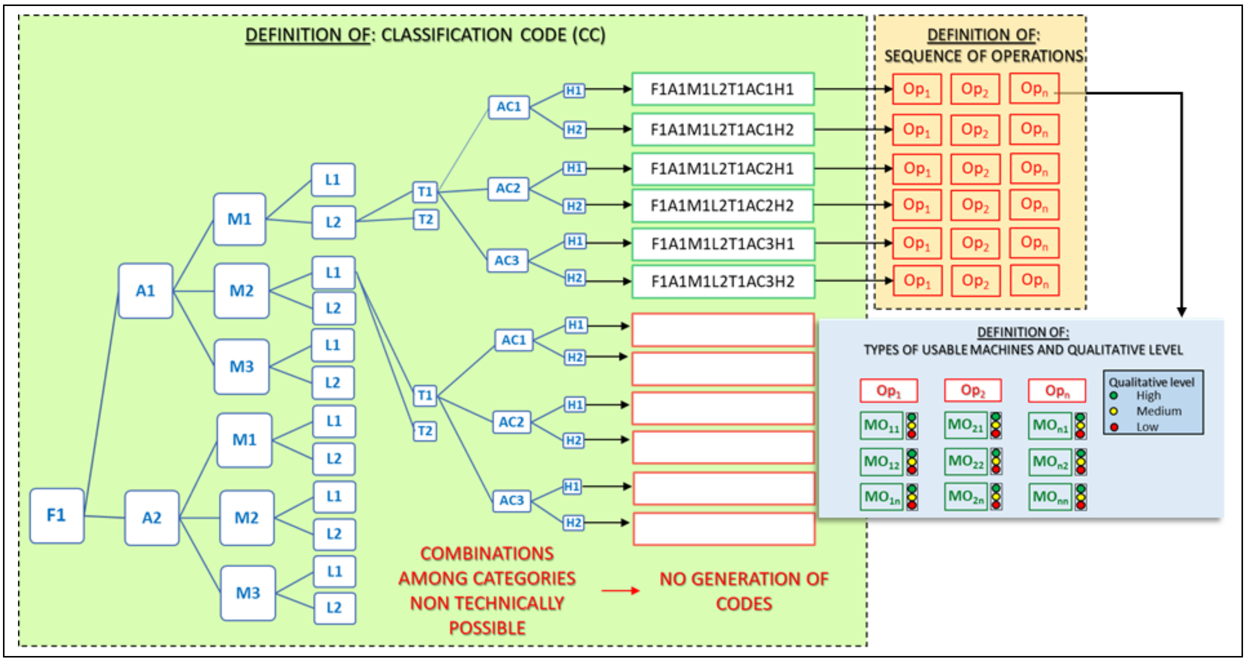


Figure 2. Schematization of the database "Definition of forestry machinery chain" (the tree-structure is not completed due to the lack of space).

6.2.1.1.1 Definition of: classification code

To develop the first table "Definition of: classification code", the most important technical parameters that affect the adoption of a generic FMC are firstly identified among the main ones defined by the literature. These parameters are aggregated into three groups of limiting factors (Perrotta, 2021):

- characteristics of the forest;
- characteristic of the production system;
- site-specific operating conditions.

The parameter related to the "characteristics of the forest" is the management system. The parameters related to the "characteristics of the production system" are:

- wood assortment;
- harvesting method;
- level of mechanization.

Finally, the parameters related to the "site-specific operating conditions" are:

- forest roads' transitability;

- forest stands’ accessibility;
- harvested merchantable mass (t·ha^{-1} DM).

Each parameter is subdivided into different categories. For the parameters n. 1 (management system), 2 (wood assortment) and 3 (harvesting method), the same categories as that reported in literature are used. In particular, for the parameter n. 1 (management system) the categories are: (i) coppice and (ii) high forest; for the parameter 2 (wood assortment) the categories are: (i) firewood, (ii) beams/poles and (iii) woodchips; for the parameter 3 (harvesting method) the categories are: (i) cut-to-length, (ii) tree length and (iii) full tree. For the parameter n. 4 (level of mechanization), 5 (forest roads’ transitability), 6 (forest stands’ accessibility) and 7 (harvested merchantable stem mass; t·ha^{-1} DM), the categories are aggregated both because detailed information is not always made available by local forestry authorities or supply chain operators, and to make the structure of the model simpler.

Forest roads’ transitability expresses the characteristics of the forest roads and is crucial to choose types and dimensions of the machines. Lombardy Region defined four “transitability classes” (TC) for forest roads, according to (Table 1):

- maximum allowable load (l_{max}; t);
- minimum width (w_{min}; m);
- prevailing and maximum slope (s_p and s_{max}, respectively; %);
- minimum turning radius (tr; m).

Starting from this classification, two TCs are defined in FOREMA v1: (i) medium-high (combination between TC I and II) and (ii) medium-low (combination between TC III and IV).

Table 1. Transitability classes according to the classification of the Lombardy Region (2008).

FOREMA v1 TCs	**Lombardy Region TCs**	**Types of Machines**	**Maximum load** l_{max} **(t)**	**Minimum width** w_{min} **(m)**	**Prevailing slope (*)** s_p **(%)**	**Maximum slope** s_{max} **(%)**		**Minimum turning radius tr (m)**
						Natural Bottom	**Stabilized Bottom**	
Medium-high	I	Truck	25	3.5	≤ 10	12	16	9
	II	Tractors and trailers	20	2.5	≤ 12	14	20	8
Medium-low	III	Small tractors	10	2.0	≤ 14	16	25	6
	IV	Small vehicles	4	1.8	> 14	> 16	> 25	< 6

(*) Not overcome for at least 70÷80% along the whole road.

The accessibility is defined as the easiness to reach each stand ("j") and depends on (Hippoliti and Piegai, 2000): (i) stand's average slope ($s_{(j)}$; %); (ii) stand's horizontal distance from the nearest forest road ($d_{R(j)}$; m); (iii) stand's difference in altitude from the nearest forest road ($d_{A(j)}$; m).

Since such a detailed information is not always made available by local forestry authorities, considering only operating conditions with a sufficient accessibility, three accessibility classes (AC) are defined (Table 2).

Table 2. Accessibility classes (striped backgrounds: conditions of insufficient accessibility).

FOREMA Accessibility class	**Stand's average slope**	**Distance from road**				**Altitude from road**
$AC_{(j)}$	**$s_{(j)}$ (%)**	**$d_{R(j)}$ (m)**				**$d_{A(j)}$ (m)**
		≤ 1000	**≤ 500**	**≤ 250**	**≤ 100**	
I	$s_{(j)} \leq 20$					-
II	$20 < s_{(j)} \leq 40$					≤ 100
	$40 < s_{(j)} \leq 60$					≤ 100
III	$s_{(j)} > 60$					≤ 100

Finally, for the harvested mass, two categories are defined in FOREMA v1, starting from the classification proposed by Marchi et al. (2013): (i) ≤ 16 $t \cdot ha^{-1}$ DM and (ii) > 16 $t \cdot ha^{-1}$ DM.

To each category of each technical parameter, a sub-code is assigned (Table 3).

Table 3. Limiting factors, technical parameters, categories, and corresponding sub-codes.

Limiting factor		**Technical Parameter**			
N°	**Name**	**N°**	**Name**	**Category**	**Sub-Code**
1	Characteristics of the forest	1	Management system	Coppice	F1
				High forest	F2
2	Characteristics of the production system	2	Wood Assortment	Firewood	A1
				Beams/poles	A2
				Woodchips	A3
		3	Harvesting Method	Cut-to-length	M1
				Tree length	M2
				Full tree	M3
		4	Level of mechanization	Low	L1
				Medium-high	L2
3	Site-specific operating conditions	5	Forest roads' Transitability	Medium-high	T1
				Medium-low	T2
		6	Forest stand's Accessibility	High (AC I)	AC1
				Medium (AC II)	AC2
				Low (AC III)	AC3
		7	Harvested merchantable mass	≤ 16 $t \cdot ha^{-1}$ DM	H1
				> 16 $t \cdot ha^{-1}$ DM	H2

The above-described technical parameters and their corresponding categories are arranged in a hierarchical tree structure; in it, each category of a parameter includes those of the subsequent ones. By combining all the categories of all the parameters, 432 combinations are obtained. These combinations represent the total number of FMCs that could be theoretically adopted, under the hypothesis that all the combinations among the categories are possible. The combinations among the categories that are really feasible are 192. Only for these combinations, FOREMA v1 combines the sub-codes of the categories to generate a "classification code" (Perrotta, 2021). If the combination among the categories is not possible, the "classification code" is not generated. For example, by selecting:

- management system → "Coppice" → F1
- wood assortment → "Firewood" → A1
- harvesting method → "Cut-to-length" → M1
- level of mechanization → "Medium-high" → L2
- forest roads' transitability → "Medium-high" → T1
- forest stand's accessibility → "High" → AC1
- harvested merchantable mass → "$\leq$ 16 t·ha^{-1} DM" → H1

The generated CC is "F1A1M1L2T1AC1H1". On the contrary, by selecting:

- management system → "Coppice" → F1
- wood assortment → "Woodchips" → A3
- harvesting method → "Cut-to-length" → M1
- level of mechanization → "Medium-high" → L2
- forest roads' transitability → "Medium-high" → T1
- forest stand's accessibility → "High" → AC1
- harvested merchantable mass → "$\leq$ 16 t·ha^{-1} DM" → H1

no code is generated, since the combination between the category "Woodchips" and the category "Cut-to-length" is not technically possible.

6.2.1.1.2 Definition of: sequence of operations

In the table "Definition of: sequence of operations", for each feasible FMC, the specific sequence of operations is defined. The sequence of the operations firstly depends on the management system that, in turn, defines the wood assortment that has to be produced and the corresponding harvesting method to adopt. All the other technical parameters influence the type of machines to use.

For the example defined in the previous paragraph (management system → "Coppice" → F1; wood assortment → "Firewood" → A1; harvesting method → "Cut-to-length" → M1; level of mechanization → "Medium-high" → L2; forest roads' transitability → "Medium-high" → T1; forest stand's accessibility → "High" → AC1; harvested merchantable mass → "≤ 16 t·ha^{-1} DM" → H1), identified by the CC "F1A1M1L2T1AC1H1", the sequence of operations is shown in Table 4.

Table 4. Sequence of operations corresponding to the CC "F1A1M1L2T1AC1H1" (Sources of pictures: Carbone and Picchio, 2019; www.atcallhire.com; www.popularmechanics.com; www.dempogroup.com; www.agroforestale-le-fontanelle.it).

Felling	Delimbing	Sectioning
		
Bunching	Extraction	Loading and transport
		

Each operation and machine is identified by an acronym (Table 5).

Table 5. Name and acronym of forestry operations and machines.

FORESTRY OPERATIONS	
Name	Acronym
Felling	FEL
Topping	TOP
Delimbing	DLB
Extraction	EXT
Sectioning	SCT
Debarking	DBK
Bunching	BNC
Chipping	CHP
Sectioning	SCT
Loading and transport	LTR
FORESTRY MACHINES	
Chainsaw	CS
Feller-buncher	FB
Feller-skidder	FSK
Harvester 4-Wheel drive	H4W
Crawler Harvester	HC
Processor	PR
Debarker	DBK
Motordebarker	MDBK
Small vehicles	SV
Small tractors	ST
Tractor + winch	TW
Pack animals	PA
Skidding with animals	SA
Cable crane (mobile drive station)	CCMS
Free sliding	FS
Grapple skidder	GSK
Skidder +winch	SKW
Traditional cable crane	CCT
Forvester	FV
Helicopter	H
Forwarder	FW
Tractor with cages	TC
Chutes	C
Lorries	LR
Graple tractor	GT
Chipper	CHP
Tractor with trailer	TT
Road train	RT

6.2.1.1.3 Definition of: types of usable machines and qualitative level

For each operation, the types of usable machines are also defined. The concept of “usability” defines “when a type of machine can be used” according to the different technical parameters. The value “1” or “0” is associated to each type of machine: “1” if the type of machine can be used for a given operation, “0” if it cannot be used. For example, for the parameter “wood assortment”, the tractor with cages is marked by a “1” for the category “firewood”, and by a “0” for the categories “woodchips” and “beams/poles”, since this type of machine is generally used only to extract firewood; for the parameter “level of mechanization”, the harvester is marked by a “0” for the category “low” and by a “1” for the category “medium-high”, since this type of machine is used only under medium-high level of mechanization.

Moreover, each type of usable machine is associated to a qualitative level, defined by an empirical value (low → -1; medium → 0; high → 1, graphically corresponding to the colors red, yellow, and green, respectively) that expresses "the ease of use of that specific type of machine" under the defined operating conditions. The concept of "ease of use" is related to the concept of "maneuverability" of the machine: if the maneuverability of the machine is high, the ease of use of that type of machine (and thus the corresponding qualitative level) is high, and vice versa.

For example, according to the parameter "forest stand's accessibility", the crawler harvester is marked by a "1" for the category "high", "0" for the category "medium" and "-1" for the category "low"; this means that the maneuverability of the harvester is "facilitated", "not affected" and "difficult", respectively, since it decreases as accessibility decreases, i.e., when the operating conditions become more difficult. In this last case it may be convenient to choose another type of machine or, in case it is not possible, a smaller machine model to increase the maneuverability under difficult operating conditions (Perrotta, 2021). Table 6 shows the qualitative levels that is assigned to the different types of machines, according to the site-specific operating conditions.

Table 6. Relation between site-specific operating conditions and use of the types of machines.

Forestry machine		Site-specific operating conditions						
		Forest roads' transitability		Forest stand's accessibility			Harvested merchantable mass ($t \cdot ha^{-1}$ DM)	
Name	Acronym	I	II	I	II	III	≤ 16	>16
Chainsaw	CS	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Yellow
Feller-buncher	FB	Green	Red	Green	Red	Red	Green	Yellow
Feller-skidder	FSK	Green	Red	Green	Red	Red	Green	Yellow
Harvester 4 wheel drive	H4W	Green	Red	Green	Red	Red	Green	Yellow
Crawler Harvester	HC	Green	Red	Green	Red	Red	Green	Yellow
Processor	PR	Green	Red	Green	Red	Red	Green	Yellow
Debarker	DBK	Green	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Motodebarker	MDBK	Yellow	Yellow	Green	Yellow	Red	Yellow	Yellow
Tractor+winch	TW	Green	Red	Green	Red	Red	Yellow	Yellow
Tractor with trailer	TT	Green	Red	Green	Yellow	Red	Yellow	Green
Tractor with cages	TC	Green	Red	Green	Yellow	Red	Yellow	Green
Small vehicles	SV	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Green
Small tractors	ST	Green	Red	Green	Yellow	Yellow	Yellow	Green
Pack animals	PA	Yellow	Yellow	Green	Green	Red	Green	Yellow
Skidding with animals	SA	Yellow	Yellow	Green	Red	Red	Green	Yellow
Free sliding	FS	Yellow	Yellow	Green	Red	Red	Green	Yellow
Cable crane (mobile station)	CCMS	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green
Grapple skidder	GSK	Green	Red	Green	Green	Red	Yellow	Yellow
Skidder + winch	SKW	Green	Red	Green	Red	Red	Yellow	Yellow
Traditional cable crane	CCT	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green
Forvester	FV	Green	Red	Green	Red	Red	Yellow	Yellow
Helicopter	H	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Forwarder	FW	Green	Red	Green	Red	Red	Yellow	Yellow
Chutes	C	Yellow	Yellow	Green	Red	Red	Yellow	Green
Lorry	LR	Green	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Chipper	CHP	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow

An example of the types of usable machines (with their corresponding qualitative levels) for each operation listed in Table 4 is shown in Figure 3.

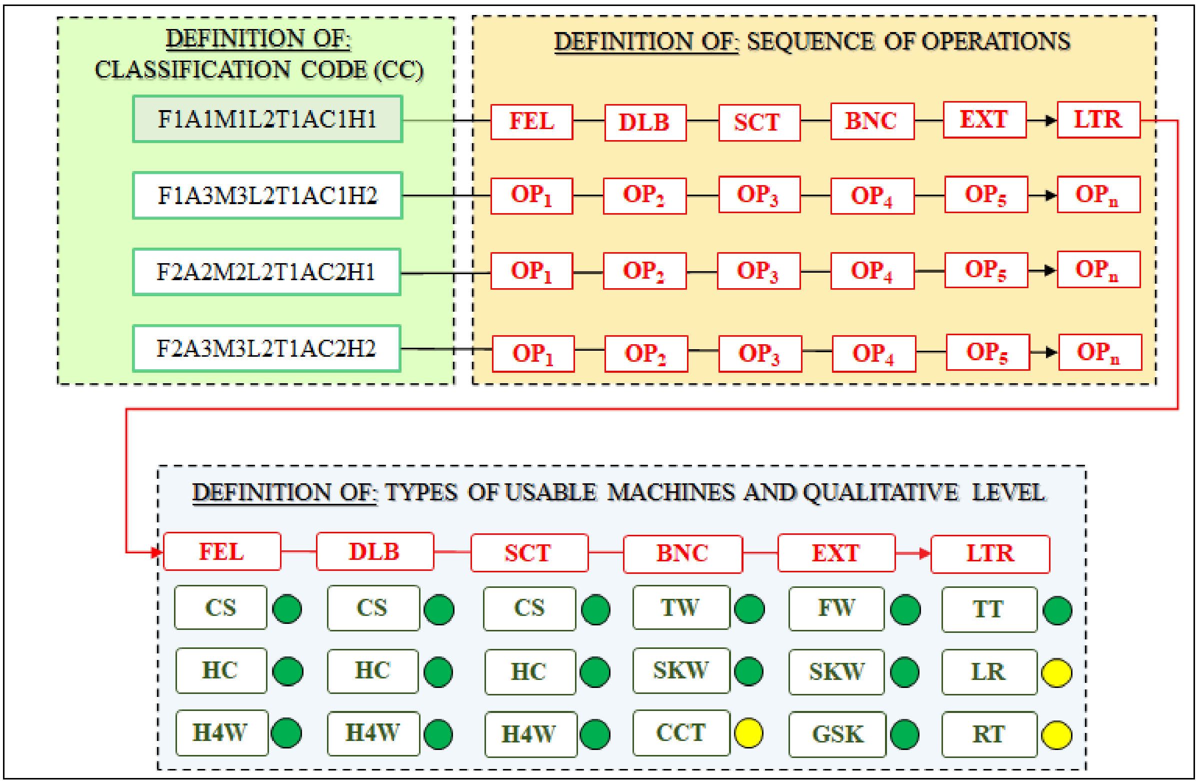


Figure 3. For each operation that compose the FMC, the table "Definition of: types of usable machines and qualitative level" defines the types of machines that can be used with their corresponding qualitative levels (not all the usable machines types are shown due to the lack of space).

6.2.1.2 Spreadsheet "User-friendly interface"

This spreadsheet is made up of three tables:

- Selection of: category for each parameter;
- Selection of: types of usable machines;
- Selected types of usable machines.

The logical framework of this spreadsheet is shown in Figure 4.

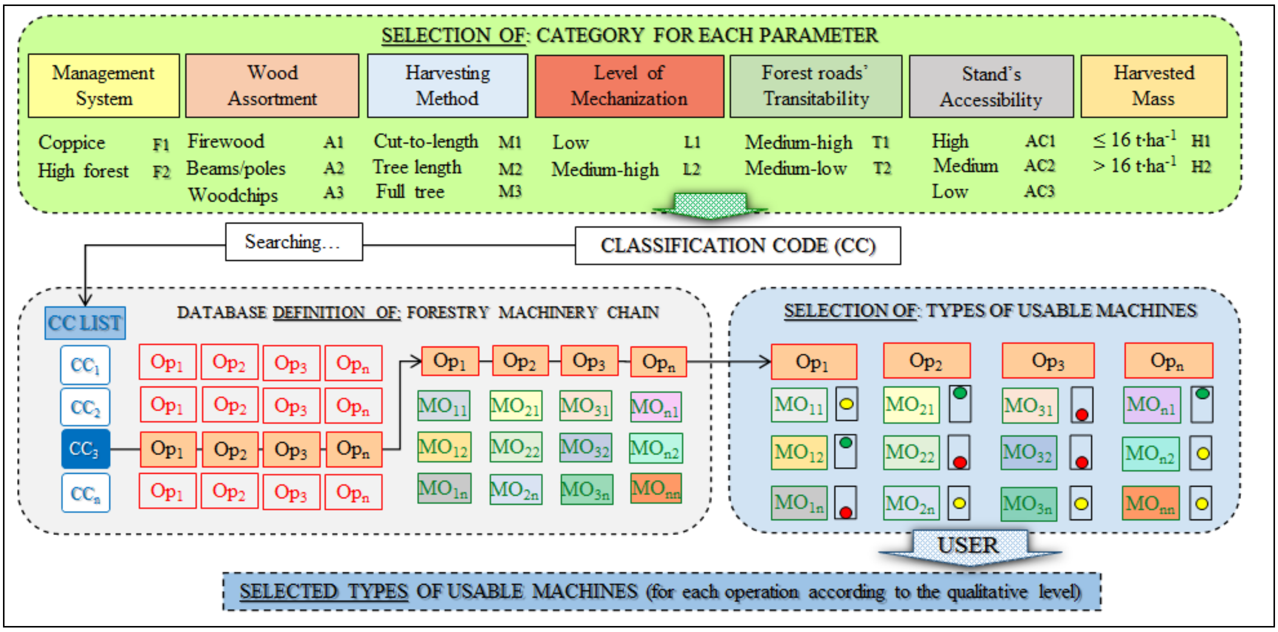


Figure 4. Logical framework of the "User-friendly interface".

6.2.1.2.1 Selection of: category for each parameter

In this table the user can select a category for each technical parameter. Through the combination of the sub-codes related to each selected category, the classification code (CC) is generated. Once the "compile" button is clicked by the user, the generated CC is searched within the list of the CC in the database "Definition of: forestry machinery chain". If the generated CC does not exist in the CC list (i.e., the categories entered by the user do not correspond to a real FMC), an error message invites the user to change the previously selected categories. Otherwise, the model proceeds to the next step. Once the real FMC is identified (through the CC) the model uses other two codes:

- alphabetical code;
- numeric code.

The alphabetical code is used to define the exact sequence of the operations that compose the selected FMC; the numeric code is used to define the exact types of usable machine for each operation with the corresponding qualitative level.

6.2.1.2.2 Selection of: types of usable machines

In this table the model allows the user to visualize and select the types of machines to be used for each operation with their corresponding qualitative level.

6.2.1.2.3 Selected types of usable machines

This table represents the final output of the model FOREMA v1 and shows the sequence of the operations that compose the selected FMC and, for each of them, the types of machines selected by the user. By clicking on the "reset" button, the sequence of the operations and the corresponding types of machines are deleted, and the user can perform a new selection. For instance, by selecting the same categories as in the example taken into account in the previous paragraphs, the CC "F1A1M1L2T1AC1H1" is generated and searched within the CC list of the database. The sequence of the operations and the corresponding types of machines and qualitative levels are shown in the table "selection of: types of usable machines". Finally, the user selects which type of machine he wants to use for each operation, and the results of the user's selection are shown.

6.2.2 Economic costs calculation

The total cost of each operation (TC_{OP}) that compose the selected FMC is computed as the sum of the fixed costs (FC_{OP}) and the variable costs (VC_{OP}) (Miyata, 1980; Brinker et al., 2002; Ackerman et al., 2014).

$$TC_{OP} = FC_{OP} + VC_{OP} \qquad \text{(Eq. 1)}$$

TC_{OP} are calculated: (i) per unit of time (€·h^{-1}), (ii) per unit of product (€·t^{-1} DM) and (iii) for the total time of the operation (cost of production; €). The total cost of the FMC (TC_{FMC}; €·h^{-1}; €·t^{-1} DM; €) – consisting in "n" operations – is calculated as:

$$TC_{FMC} = \sum_{i \to 1}^{n} TC_{OPi} \qquad \text{(Eq. 2)}$$

FC_{OP} includes:

- financial depreciation;
- insurance;
- supervision, management, and administration;
- garaging.

VC_{OP} includes:

- repair and maintenance;
- fuel, oil, and lubricants;

- labor.

If an operation is performed by using a base machine (e.g., a tractor) coupled with an implement (e.g., a trailer), the fixed and the variable costs are calculated separately for the base machine and the implement, since they are characterized by a different service life, economic life, and annual use (Ackerman et al., 2014). The costs of the implement are computed in the same way as the base machine, except for fuel and lubricants – that are not present – and labor, which is ascribed to the base machine.

Financial depreciation is used when the purchase is made by credit from the financial market. The capital is spread over the useful life of the base machine (and implement, if present), considering the related interest costs that are defined in the loan agreement. The annual depreciation is calculated for each machine and implement according to Carbone (2008), by using a fixed interest rate for each type of machine and implement, and a salvage value computed according to Lazzari and Mazzetto (2005). The cost of insurance includes protection against fire, theft, and other damages; the cost of supervision, management and administration covers the cost required to set goals and coordinate the work, ensuring that it is properly performed. Both these costs are computed for machine and implement as a fraction of the purchase price (FAO, 1974).

The cost of garaging expresses the cost of keeping the machine and the implement in an appropriate repaired place when they are not working, to avoid damage and loss of efficiency. This cost is quantified by multiplying the required area ($m^2 \cdot yr^{-1}$) of the machine and implement for the cost per unit of area (€$\cdot m^{-2}$) (Carbone, 2008).

The cost of repair and maintenance includes both the cost for the simple maintenance, as well as that for the periodic overhaul of engine, transmission, clutch, brakes, tire (or track) replacement and other major equipment and is quantified as a fraction of the depreciation (Akay, 1998; Brinker, 2002).

The cost of fuel is computed by considering the maximum engine power of the machine (kW), the specific fuel consumption, the average engine load (% of the maximum engine power) and the fuel price (€$\cdot dm^{-3}$), as reported in Lazzari and Mazzetto (2005). The cost of oil and lubricants (i.e., cost for engine oil, transmission oil, hydraulic oil, grease, and filters) is estimated as the product between the lubricant price (€$\cdot dm^{-3}$) and the lubricant consumption. This latter is assumed equal to 15% of fuel consumption (ASABE, 2006). Finally, the labor costs includes basic wages of workers plus overheads and fringe costs (insurance, social security, and welfare charges).

6.3 Case Study

The described approach was applied for a Case Study concerning the collection of woodchips from a coppice stand in the Italian Alps for energy generation. The characteristics of the stand are shown in Table 7.

Table 7. Characteristics of the stand of the Case Study.

Technical parameter	Category
Management system	Coppice
Wood assortment	Woodchips
Harvesting method	Full-tree
Level of mechanization	Medium-high
Forest road's transitability	Medium-high
Stand's accessibility (*)	High
Harvested mass ($t \cdot ha^{-1}$ DM) ($)	12.2
Other data	
Forest area (ha)	5
Species	*Fagus sylvatica* L.

(*) It was defined by assuming an average slope of 10% and a distance from the nearest forest road of 100 m. ($) It was calculated by considering an average wood basic density for *Fagus sylvatica* L. equal to 0.61 $t \cdot m^{-3}$ DM and a harvested volume of 20 $m^3 \cdot ha^{-1}$.

According to the technical parameters and categories reported in Table 7, the operations and the types of machines resulted from the model FOREMA v1 are shown in Table 8.

Table 8. Sequence of operations, types of usable machines and selected types of usable machines.

Operation		Types of usable machines	Selected types of usable machine (user)
N.	Name		
1	Felling	Chainsaw, harvester 4WD, crawler harvester, feller buncher, feller skidder, forvester.	Chainsaw
2	Bunching & Extraction	Grapple tractor, tractor with winch, grapple skidder, skidder with winch, forvester, forwarder, cable crane with mobile drive station, traditional cable crane.	Tractor with winch
3	Chipping	Chipper	Chipper
4	Loading & transport	Tractor with trailer	Tractor with trailer

For each types of machine, the used models are shown in Table 9.

Table 9. Sequence of operations, selected types of usable machines and used models.

Operation	Selected types of usable machine	Used machines' model
Felling	Chainsaw	Stihl MS 362 C-M
Bunching & Extraction	Tractor with winch	4 WD Fendt 312 Vario (tractor) + Shwarz EGV 105 AHK SG (winch)
Chipping	Chipper	Gandini 40-60 TTS (*)
Loading & transport	Tractor with trailer	4 WD Valtra T 174 (tractor) + D'Eusanio DRR 140 (trailer)

(*) The machine is coupled through the PTO to a tractor which is of the same model of those used for transport.

Before computing the economic costs, preliminary calculations were performed to define the total required time (h) for each operation, the productivity ($m^3 \cdot h^{-1}$; $t \cdot h^{-1}$ DM), and the corresponding number of machines and workers (Table 10). It was assumed that bunching & extraction, chipping, and loading & transport occurred simultaneously. For bunching & extraction and chipping this assumption is reasonable since, at the landing, the available space to stock the extracted wood is generally not high in mountainous areas and, in any case, it is advisable to chip the biomass as soon as possible to avoid that storing felled trees causes a deterioration of the physical characteristics of the wood. For chipping and loading & transport, the simultaneity is essential, both to avoid delay times, and because chipping occurs when also trailers for transport are present at the landing.
For each operation, the useful time ($h \cdot worker^{-1}$) was firstly calculated as the product between: (i) useful days, (ii) total working hours per worker per shift ($h \cdot worker^{-1} \cdot shift^{-1}$) and (iii) number of shifts per day ($shifts \cdot day^{-1}$).

Table 10. Productivity, total required time, number of required machines and workers for each operation.

Data	**Unit**	**Operations and machines**			
		Felling	**Bunching & extraction**	**Chipping**	**Loading & Transport**
		Chainsaw	**Tractor with Winch**	**Tractor with Chipper**	**Tractor with trailer**
Useful days	Days	5.0	1.0	1.0	1.0
N. working hours per worker per shift	$h \cdot worker^{-1} \cdot shift^{-1}$	8.0	8.0	8.0	8.0
N. shifts per day	$shifts \cdot day^{-1}$	1.0	1.0	1.0	1.0
Useful time	$h \cdot worker^{-1}$	40.0	8.0	8.0	8.0
Gross productivity (1 machine)	$m^3 \cdot h^{-1}$	1.0	12.5	12.5 (*)	3.1
Gross productivity (1 machine)	$t \cdot h^{-1}$ DM	0.6	7.6	7.6	1.9
Total required time	h	100.0	8.0	8.0	32.1
N. of required machines/implements	-	3	1	1	4
Gross productivity (total)	$m^3 \cdot h^{-1}$	3	12.5	12.5	12.5
Gross productivity (total)	$t \cdot h^{-1}$ DM	1.8	7.6	7.6	7.6
N. of workers (1 machine)	-	1	2	3	1
N. of workers (total)	-	3	2	3	4
Time associated to 1 machine	h	33.3	8.0	8.0	8.0

(*) Since chipping occurred simultaneously to bunching & extraction, the productivity of this operation was set equal to that of the previous one and, therefore, was expressed as $m^3 \cdot h^{-1}$ of stem and branches. By assuming a volumetric coefficient (i.e., ratio between the bulk volume of woodchips and the volume of stem and branches) equal to 3, the productivity of chipping expressed as woodchips was equal to 37.5 $m^3 \cdot h^{-1}$, approximately. Therefore, the costs for this operation was calculated by taking into account a chipper with a productivity of 37.5 $m^3 \cdot h^{-1}$ of woodchips. Productivity values were obtained from commercial catalogues.

For felling, the total required time was computed as the ratio between the total mass to be harvested (61 t DM) and the average productivity related to a single chainsaw. Productivity is mainly affected by trees' species, dimension and weight, cutting intensity, wood assortments, stand's slope, presence of obstacles, climate, as well as position and ability of workers (Hippoliti and Piegai, 2000; Blanch, 2010; Verani et al., 2017; Unrau et al., 2018). In natural coppice stands, when the cut-to-length method is adopted for firewood production, small stem size, uncomfortable working positions, and the need of cutting stems into manageable lengths cause a low productivity of felling operation, i.e., between 0.3 and 1.4 $m^3 \cdot h^{-1} \cdot worker^{-1}$ (Unrau et al., 2018). When the full-tree method is adopted, directional felling through chainsaw can increase the productivity to values ranging between 1 and 4 $m^3 \cdot h^{-1} \cdot worker^{-1}$ (Unrau et al., 2018). Hippoliti and Piegai (2000) reported general values of productivity for felling and processing in coppices according to species, wood characteristics and type of wood cuts (i.e., final cuts on mature stands; conversion to high forests or thinning) and expressed as steric cubic meter per day per worker ($sm^3 \cdot d^{-1} \cdot worker^{-1}$). For final cuts, values ranged between 2.5-4.0 $sm^3 \cdot d^{-1} \cdot worker^{-1}$ (dirty coppices with poor physical characteristics) to 8.0-15.0 $sm^3 \cdot d^{-1} \cdot worker^{-1}$ (old coppices of *Castanea sativa* Mill., *Fagus sylvatica* L. and *Quercus cerris* L.). For conversion to high forests or thinning, productivity values ranged between 2.0-3.0 $sm^3 \cdot d^{-1} \cdot worker^{-1}$ (coppices with mixed species) to 4.0-5.0 $sm^3 \cdot d^{-1} \cdot worker^{-1}$ (old coppices of *Castanea sativa* Mill., *Fagus sylvatica* L. and *Quercus cerris* L.). Spinelli et al. (2016) performed a regression analysis showing that, for felling with chainsaw, the worker productivity for traditional coppice stands ($m^3 \cdot h^{-1} \cdot worker^{-1}$) was strongly affected by the volume of the harvested wood ($m^3 \cdot ha^{-1}$). For a volume equal to 20 $m^3 \cdot ha^{-1}$, approximately, like the one considered in this Case Study, the productivity for felling with chainsaw reached 1 $m^3 \cdot h^{-1} \cdot worker^{-1}$, approximately. Considering all these elements, and since specific measured data were not available for this Case Study, the productivity of felling with chainsaw was defined as input data, and equal to 1 $m^3 \cdot h^{-1}$.

For bunching & extraction and loading & transport, the total required time and the productivity were calculated by considering several parameters and the time subdivision according to the CIOSTA methodology for the agricultural machines (Reboul, 1964) (Table 11 and Table 12). Since it was assumed that bunching & extraction, chipping, and loading & transport occurred simultaneously, the total required time related to 1 machine was the same for all the three operations, i.e., 8 h. Therefore, the total time associated to the whole FMC reached 41.3 h.

Table 11. Parameters used to compute the total required time and the productivity for bunching & extraction.

Bunching distance	m	20.0
Worker's speed	$m \cdot s^{-1}$	1.0
Speed of rope winding on the winch (*)	$m \cdot s^{-1}$	1.2
Extraction distance	m	100.0
Forward speed	$m \cdot s^{-1}$	2.0
Return speed	$m \cdot s^{-1}$	3.0
Loaded wood volume per trip (#)	$m^3 \cdot trip^{-1}$	2.0

N. of trips	-	50
Time for rope winding on the winch	s	17
Time for transfer (travel loaded)	s	50
Time of effective work (TE; rope winding + travel loaded)	h	0.02
Additional times (TA)		
Machine/implement arrangement on field	s	425
Time of transfer (travel unloaded)	s	33
Turning	s	0
On-field maintenance ($)	s	0.67
Delays (avoidable and not-avoidable) (@)	s	0.0
Rest	s	0.0
Other times not included in the previous ones (**)	s	50
Total	h	0.14
Total required time (TE + TA)	h	8.0
Gross productivity (1 machine only)	$m^3 \cdot h^{-1}$	12.5

(*) Related to stems of medium dimensions (Blanch, 2010); (#) Not having specific data related to the used winch model, an average value was assumed (Blanch, 2010); Similar values are also reported in other studies on coppice stands where the full-tree method is applied for wood extraction (Spinelli and Magagnotti, 2012); ($) Assumed equal to 1% of the time of effective work; (@) They include: (i) not-avoidable times due to accidental causes (e.g., mechanical components breaking) or operators' personal needs and (ii) avoidable times (idleness or bad organization of the work); (**) They include: (i) time required for the worker to reach the felled trees (20 s), (ii) time of rope hooking (20 s) and (iii) time of rope unhooking at the landing (10 s).

The main parameters affecting the productivity of wood extraction are the extraction distance and the average loaded volume per trip (Spinelli and Magagnotti, 2012). The value of productivity here estimated, i.e., 12 $m^3 \cdot h^{-1}$, is considerably higher than that reported in other studies in Italy. Spinelli and Magagnotti (2012), for example, performed three different tests in three different locations in Central Italy to calculate the productivity of wood extraction in coppice stands where the full-tree method is applied. They found that the productivity values ranged between 1.5 and 7.9 $m^3 \cdot h^{-1}$ with an average loaded volume of wood ranging between 1.1 and 3.0 $m^3 \cdot trip^{-1}$.

Table 12. Parameters used to compute the total required time and the productivity for loading & transport.

Transport distance (to the final user)	km	10.0
Forward speed	$km \cdot h^{-1}$	15.0
Return speed	$km \cdot h^{-1}$	20.0
Trailer bulk volume	m^3	16.0
Trailer filling coefficient	%	100
Volumetric coefficient	-	3
N. of trips	-	19
Time of effective work (TE; travel loaded)	h	0.67
Additional times (TA)		
Machine/implement arrangement on field	s	0
Time of transfer (travel unloaded)	s	1800

Turning	s	0
On-field maintenance ($)	s	24
Delays (avoidable and not-avoidable) (@)	s	0.0
Rest	s	0.0
Other times not included in the previous ones (**)	s	1881
Total	h	1.03
Total required time (TE + TA)	h	32.1
N. of required tractors (and trailers)	-	4
Gross productivity (total)	$m^3 \cdot h^{-1}$	12.5

($) Assumed equal to 1% of the time of effective work; (@) Defined as indicated in Table 11; (**) They include: (i) time for trailer filling (1521 s) and (ii) time for trailer emptying (360 s).

Table 13 shows the main technical and economic parameters used to calculate the economic costs of the operations.

Table 13. Technical and economic parameters used to calculate the economic costs.

Technical and economic Parameters	Unit	Machines and implements					
		Chainsaw	**Tractor**	**Winch**	**Chipper**	**Tractor**	**Trailer**
Producer	-	Stihl	Fendt	Shwarz	Gandini	Valtra	D'Eusanio
Model	-	MS 362 C-M	Fendt 312 Vario	EGV 105 AHK SG	40-60 TTS	T 174	DRR 140
Maximum engine power (P_M)	kW	3.5	90.0	-	130.0 ($)	130.0	-
Purchase price (P)	€	1185	130882	14750	25000	133500	11600
Salvage value rate	% P	20.0%	12.5%	10.0%	20.0%	12.5%	18%
Interest rate	%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Insurance rate	% P	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Supervision and management rate	% P	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Area for garaging	$m^2 \cdot yr^{-1}$	0.5	11.0	1.6	7.0	13.0	12.0
Cost per unit of area of garaging	$€ \cdot m^{-2}$	3.6	3.6	3.6	3.6	3.6	3.6
Operator wage	$€ \cdot h^{-1}$	15.0	15.0	-	15.0	15.0	-
Required Workers (1 machine)	-	1	2	-	3	1	-
Repair and maintenance rate	% D (*)	100%	100%	100%	100%	100%	100%
Average engine load (% P_M)	%	70%	40%	-	40%	40%	-
Fuel price	$€ \cdot dm^{-3}$	1.5	1.0	-	1.0	1.0	-
Lubricant consumption rate	% FC (#)	15%	15%	-	15%	15%	-
Lubricant price	$€ \cdot dm^{-3}$	4.0	4.0	-	4.0	4.0	-
Service life	H	3175	12000	6000	10000	12000	3000
Economic life	Yr	3	12	8	10	12	12
Annual use	$h \cdot yr^{-1}$	400	1000	250	800	1000	250

(*) D = depreciation; (#) FC = fuel consumption; ($) It is referred to the maximum engine power of the coupled tractor.

Table 14 shows the references used to define the values of the parameters reported in Table 13.

Table 14. References considered for the definition of the values of the parameters reported in Table 13.

Technical and economic Parameters	**Unit**	**Machines and implements**					
		Chainsaw	**Tractor**	**Winch**	**Chipper**	**Tractor**	**Trailer**
Producer	-	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue
Model	-	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue
Maximum engine power (P_M)	kW	Catalogue	Catalogue	-	-	Catalogue	-
Purchase price (P)	€	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue
Salvage value rate	% P	Akay (1998)	Lazzari and Mazzetto (2005)	Akay (1998)	Akay (1998)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)
Interest rate	%	Verani et al. (2017)	Verani et al. (2017)	Verani et al. (2017)	Verani et al. (2017)	Verani et al. (2017)	Verani et al. (2017)
Insurance rate	% P	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)
Supervision and management rate	% P	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)
Area for garaging	$m^2 \cdot yr^{-1}$	Pignatti et al. (2019)	Catalogue	Catalogue	Catalogue	Catalogue	Catalogue
Cost per unit of area of garaging	$€ \cdot m^{-2}$	Carbone (2008)	Carbone (2008)	Carbone (2008)	Carbone (2008)	Carbone (2008)	Carbone (2008)
Operator wage	$€ \cdot h^{-1}$	Verani et al. (2017)	Verani et al. (2017)	-	Verani et al. (2017)	Verani et al. (2017)	-
Workers (for 1 machine)	-	Verani et al. (2009)	Verani et al. (2017)	-	Verani et al. (2017)	Verani et al. (2017)	-
Repair and maintenance rate	% D (*)	Akay (1998)	Akay (1998)	Akay (1998)	Brinker (2002)	Akay (1998)	Akay (1998) (@)
Average engine load (% P_M)	%	Triplat et al. (2020)	Triplat et al. (2020)	-	Triplat et al. (2020)	Triplat et al. (2020)	-
Fuel price	$€ \cdot dm^{-3}$	Market	Market	-	Market	Market	-
Lubricant consumption rate	% FC (#)	ASABE (2006)	ASABE (2006)	-	ASABE (2006)	ASABE (2006)	-
Lubricant price	$€ \cdot dm^{-3}$	Market	Market	-	Market	Market	-
Service life	H	Calvo et al. (2013)	Lazzari and Mazzetto (2005)	Blanch (2010)	Blanch (2010)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)
Economic life	Yr	Blanch (2010)	Lazzari and Mazzetto (2005)	Blanch (2010)	Blanch (2010)	Lazzari and Mazzetto (2005)	Lazzari and Mazzetto (2005)
Annual use	$h \cdot yr^{-1}$	Blanch (2010)	Pignatti et al. (2019)	Verani et al. (2017)	Verani et al. (2017)	Pignatti et al. (2019)	(Pignatti et al. 2019) ($)

(*) D = depreciation; (#) FC = fuel consumption; (@) Since specific values were not made available by the literature, the rapair and maintenance rate was set equal to that of the winch.

6.4 Results and discussion

Figure 5 shows the cost per unit of time (€·h^{-1}) of the operations that compose the selected FMC.

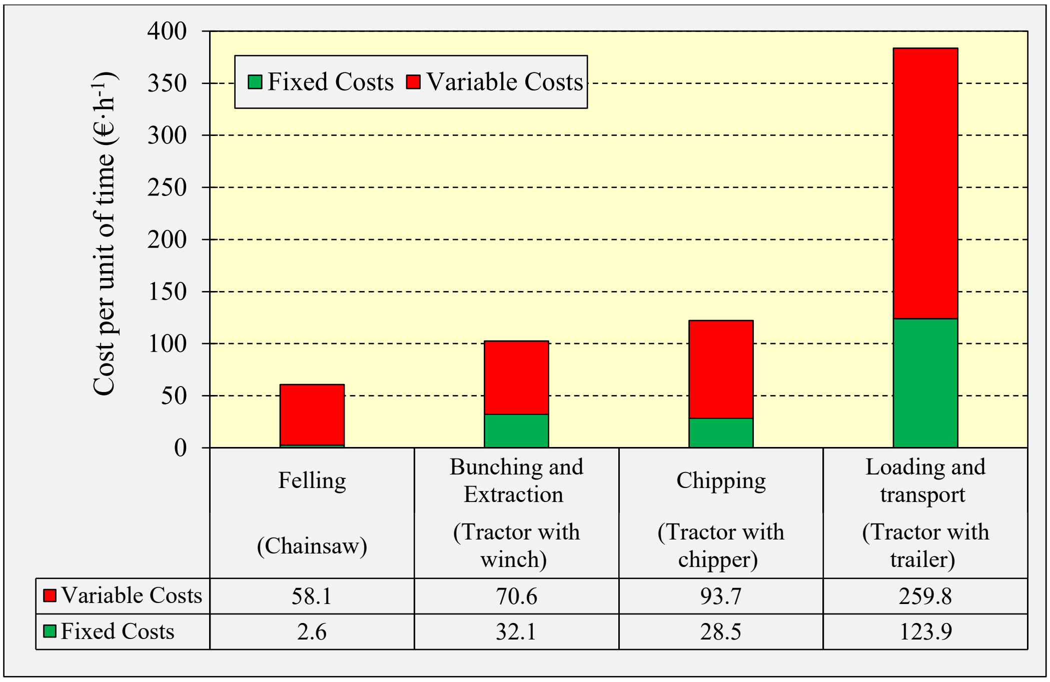
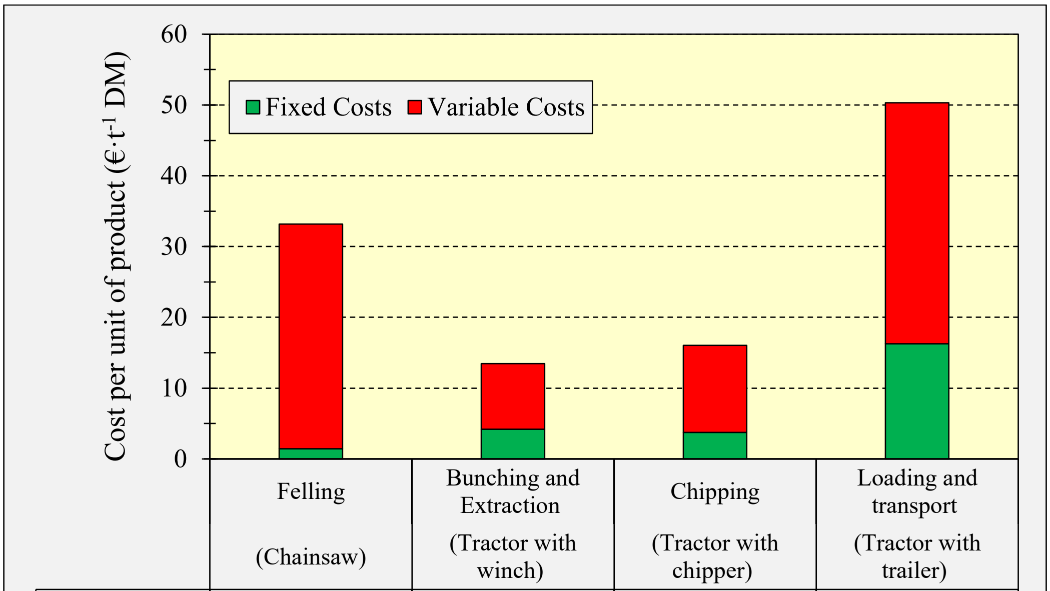


Figure 5. Cost per unit of time (€·h^{-1}) for each operation that compose the FMC.

The cost per unit of time of felling was equal to 60.7 €·h^{-1} (20 €·h^{-1} for each chainsaw; 4.3% fixed costs and 95.7% variable costs), and 74% was due to labor. The cost per unit of time for bunching & extraction amounted to 102.7 €·h^{-1}; the cost for chipping was double of that of felling (122.2 €·h^{-1}) since the annual cost of chipping was 4 times higher (24300 €·yr^{-1} and 97750 €·yr^{-1}, respectively) but the hours of annual use of chipper were only 2 times higher than that of the chainsaws (800 h·yr^{-1} and 400 h·yr^{-1}, respectively).

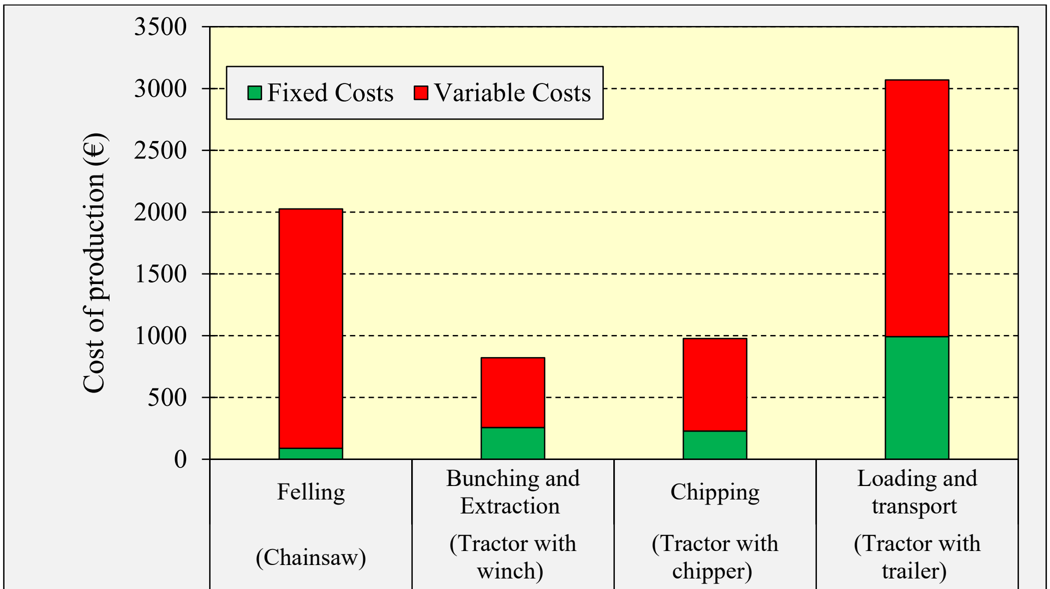
For loading & transport, the cost per unit of time amounted to 383.7 €·h^{-1} because 4 tractors and 4 trailers were required. The number of trips was high since, in the conditions that characterized the Case Study, it was reasonable to assume that medium-small sized trailers were used for wood transport over mountainous roads.

Figure 6 shows the cost per unit of product (€·t^{-1} DM), whereas Figure 7 shows the cost of production (€) for each operation.



	Felling (Chainsaw)	Bunching and Extraction (Tractor with winch)	Chipping (Tractor with chipper)	Loading and transport (Tractor with trailer)
Variable Costs	31.8	9.3	12.3	34.1
Fixed Costs	1.4	4.2	3.7	16.3

Figure 6. Cost per unit of product (€·t^{-1} DM) for each operation that compose the FMC.



	Felling (Chainsaw)	Bunching and Extraction (Tractor with winch)	Chipping (Tractor with chipper)	Loading and transport (Tractor with trailer)
Variable Costs	1937.2	564.8	749.5	2078.4
Fixed Costs	87.2	256.8	228.0	991.4

Figure 7. Cost of production (€) for each operation that compose the FMC.

For felling, the cost of production was higher than that of bunching & extraction and chipping since 3 chainsaws were used for the operation and the total required time was 33 h *vs* 8 h for the other two operations. However, since the total gross annual productivity of felling performed with 3 chainsaws was considerably lower than the annual productivity of the other two operations (732.0 t·yr^{-1} DM, 1906.3 t·yr^{-1} DM and 6100.0 t·yr^{-1} DM for felling, bunching & extraction, and chipping, respectively) the cost per unit of product was higher (33.2 €·t^{-1} DM, 13.5 €·t^{-1} DM and 16.0 €·t^{-1} DM respectively).

For chipping, the cost per unit of product was slightly higher than that of bunching & extraction, but lower than that of felling and loading & transport since the hours of annual use of the chipper were the highest (800 $h \cdot yr^{-1}$) and, therefore, also the total annual productivity.

The total gross annual productivity ($t \cdot yr^{-1}$ DM) of loading & transport was equal to that of bunching & extraction but, despite this, the use of 4 tractors and 4 trailers, the high number of trips and the covered distance caused a higher cost per unit of product (50.4 € t^{-1} DM for loading & transport; 13.5 €$\cdot t^{-1}$ DM for bunching & extraction). Table 15 shows the results related to the whole FMC.

Table 15. Costs related to the whole FMC. For each category of cost (cost per unit of time, per unit of product and of the production) the fixed and the variable costs were computed as the sum of fixed and variable costs of each operation.

Type of cost	Cost per unit of time (€$\cdot h^{-1}$)	Cost per unit of product (€$\cdot t^{-1}$ DM)	Cost of production (€)
Fixed costs	187.1	25.6	1563.3
Variable costs	482.2	87.4	5329.9
Total costs	669.3	113.0	6893.2

For felling with chainsaw, Cataldo et al. (2020) reported a cost per unit of time in Southern Italy equal to 25.1 €$\cdot h^{-1} \cdot worker^{-1}$, with a cost of labor (1 worker) of 21 €$\cdot h^{-1}$. For short rotation coppice of eucalyptus for firewood production, Pignatti et al. (2019) reported a cost per unit of time of 17.4 €$\cdot h^{-1} \cdot worker^{-1}$, with a cost of labor of 15 €$\cdot h^{-1}$. In Verani et al. (2017), the cost per unit of time was 18.7 €$\cdot h^{-1} \cdot worker^{-1}$, with the cost of labor equal to 15 €$\cdot h^{-1}$. In Picchio et al. (2020) the cost per unit of time was 23.4 €$\cdot h^{-1} \cdot worker^{-1}$ (cost of labor of 15 €$\cdot h^{-1}$)

For bunching & extraction with 1 tractor and 1 winch, Cataldo et al. (2020) reported a cost of 68.7 €$\cdot h^{-1} \cdot worker^{-1}$, whereas in this study a cost equal to 102.7 €$\cdot h^{-1} \cdot worker^{-1}$ was obtained. In Pignatti et al. (2019), the cost per unit of time was 40.9 €$\cdot h^{-1} \cdot worker^{-1}$, whereas Verani et al. (2017) reported a cost per unit of time equal to 35.4 €$\cdot h^{-1} \cdot worker^{-1}$.

The difference of the cost per unit of time was higher for bunching & extraction rather than for felling because the power – and therefore the purchase price – of the different models of chainsaws were much less variable than the power and purchase price of the tractors used for bunching & extraction.

The obtained results must be validated through experimental tests to collect information on the real operating conditions in which the machines are used, and, consequently, on the corresponding economic costs.

Overall, a general discussion on the presented approach can be made. When developing an approach for users with different needs (e.g., research, planning, management), some simplifications are needed. First of all, some technical parameters originally included in FOREMA v1 (e.g., species) were subsequently excluded. Including the species would lead in many cases to the generation of several CC identical to each other, with the result that the structure of the model would become more complex without providing any additional useful information. Other technical parameters considered important by the literature (e.g., average diameter of the trees and wood quality) were excluded mainly because such information is not always made available for a given stand. Since also these parameters affect the selection of the types of machines, they can be considered for future improvements of FOREMA v1.

Furthermore, other aspects should be taken into consideration, in particular when heavy machines are used. Recent studies showed that wood collection can cause impacts on the soil for several years (Cambi et al., 2016). Under wet conditions, soils rich in clay and loam are generally highly susceptible to compaction, offering low traction for wheel-based machines; moreover, erosion can occur if the soil surface is not properly covered with branches or other logging residues. On the contrary, very dry sandy soils are difficult for wheel-based machines, often making it necessary to irrigate the soil surface to avoid the machines to get stuck. Therefore, both clay/loam and sandy soils can lead to restrictions when selecting the most appropriate types of machines to use (Fenner, 1996; Heinimann, 1997). Moreover, it should be taken into consideration that wood collection generally causes changes in litter quantity and quality, nutrient availability, and vegetation (Keenan and Kimmins, 1993; Jurgensen et al., 1997).

6.5 Conclusion

In recent decades, the growing interest in using renewable energy sources to replace fossil fuels has led to a very intensive use of the forests, increasing the human pressure on the environment. Wood collection represents an essential part of every forest-wood supply chain and, in the context of sustainable forest management, is a key issue through which the human impact on the ecosystems can be reduced (Dietz et al., 1984). In the long term, a proper planning of wood collection can help to reduce environmental degradation, as well as the injury to the forest workers while improving, at the same time, the utilization of natural resources (McEvoy, 2004).

At this purpose, all the operations needed for wood collection have to be thoroughly planned and executed to limit any damages on the ecosystems, putting at risk sustainability issues of the whole chain. Planning of wood collection occurs both at the macroscale (e.g., landscape level), by taking into account parameters such as the mass to be collected and the areas, and at the microscale (e.g., stand level), where other parameters, such as the accessibility and the characteristics of the stands have to be considered (Nutto et al., 2016).

In the Italian Alps, planning of wood collection at the stand level is crucial to combine information on forest management and ecology with information related to forestry machines and mechanization.

One of the most important steps is the selection of the most appropriate machines to adopt for each operation that compose the whole FMC.
The aim of the study was to develop an innovative approach to select the most suitable FMC to adopt for wood collection at the stand level and compute, at the same time, the economic costs of each operation that compose the selected chain.
To make this selection feasible, a MS Office Excel-based model called FOREstry MAchinery chain selection (FOREMA v1) was developed. The model is made up of a database and a user-friendly interface. In the database, the feasible FMCs are defined by combining the categories that compose seven technical parameters that characterize the stand: (i) management system, (ii) wood assortment, (iii) harvesting method, (iv) level of mechanization, (v) stand's accessibility, (vi) forest roads' transitability and (vii) harvested merchantable mass ($t \cdot ha^{-1}$ DM). For each feasible FMC, FOREMA v1 defines the sequence of operations and the types of machines that can be used. In the second spreadsheet, the user select the categories for each parameter and choose the types of machines to use according to the suggestions of the model. Therefore, the final decision on the types of machines to use has to be made by the used and, for each operation, only one type of machine can be selected.
It should be underlined again that FOREMA v1 does not provide information about the specific models of machines and their characteristics, since this depends on the technical and organizational factors of the logging company. This information must be provided by the user when the costs are calculated. For each operation, the total cost is given by the sum of fixed and variable costs. The total cost related to the whole FMC is given by the sum of the total costs related to each operation.
The described approach was applied for a Case Study concerning the collection of the whole tree from a coppice stand to produce woodchips for energy generation, by assuming that the operations of bunching&extraction, chipping and loading&transport occurred simultaneously.

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Chapter 7 – Conclusion and future research

The importance of forests in supporting human needs is considerable. At the same time, forests are continuously under pressure due to the climate change and the growing demand of the society for natural resources. Forests are rich in biodiversity and value for recreation, they regulate water flow, promote soil formation, absorb the atmospheric C by stocking it into the above and belowground biomass and, at the same time, they make available renewable materials for the production of long life-cycle products or energy generation.

In the context of the current climate change, the **quantification of forest wood** and the corresponding **C stock** represents one of the most important goals of forest management. This is particularly important for the **local scale**, where forests are an essential part of the ecosystems and heavily contribute to the local economy.

It is therefore necessary to **develop models** that provide information, on one hand, on the mass of wood and C that forests can stock and, on the other hand, on the mass of wood that can be collected for building and energy purposes.

In Italy, forest management at the local scale is implemented through the **Forest Management Plans** (FMP) which defines, for each stand, the silvicultural treatments to carry out over a given period of time, while maintaining the productive, environmental, naturalistic, and social functions. For each stand, the quantitative data that is always made available is the total merchantable stem volume; more specific data, such as the number of trees, the volume of each tree, the average diameter, or the basal area, are not always made available.

Under these conditions, using single-tree level models is not always possible and the **only feasible solution** consists in developing models where the **reference unit** is the **stand**.

To meet this objective, the **first activity** of this PhD Thesis concerned the development of a **stand-level model** called **WOody biomass and Carbon ASsessment (WOCAS)**. The first version of the model (WOCAS v1) was improved into a second version (WOCAS v2) to compute – by using FMPs data – the mass of wood ($t \cdot yr^{-1}$ of dry matter, DM) and C ($t \cdot yr^{-1}$ C) in different ecosystem compartments from the year in which the FMPs entry into force until a predefined reference year.

At the same time, a methodology was implemented into WOCAS v2 to quantify the mass of potentially available logging residues ($t \cdot yr^{-1}$ DM) for energy generation, the corresponding potentially generated energy ($GJ \cdot yr^{-1}$) and the potentially avoided CO_2 emissions into the atmosphere ($t \cdot yr^{-1}$ CO_2) related to the combustion process, under the assumption that wood replaces non-renewable energy sources.

Regarding the computation of wood and C stock, the **improvements introduced into WOCAS v2** are different; the main one consists in the calculation of the gross annual increment ($t \cdot yr^{-1}$ DM) of the stand by using a **theoretical non-linear function** based on the merchantable stem mass, without considering the age. This is a big advantage compared to age-dependent functions on which other models are based, since it allows estimating the increment for both even-aged and uneven-aged stands. However, it is crucial to underline that the **validation** of the results for the Case Study Area was possible only by comparing the gross annual increment provided by the FMPs (which is assumed as constant over time) with the one predicted by the model. For the merchantable stem mass, the validation at the stand level is currently not possible since updated FMPs data are not available yet.

Another aspect that should be underlined is that the application of WOCAS v2 to the Case Study Area was performed without taking into account the natural disturbances, since no data were made available by the FMPs. This aspect must be taken into consideration for future research, since these processes considerably affect the growth of the forest and C dynamic.

The mass of potentially available residues for the Case Study Area was firstly computed, as a preliminary assessment, only according to the stand's function and the stand's management system. The results were further investigated by taking into account also the stand's accessibility and the forest roads' transitability. To do this, FMPs data coming from WOCAS v2 were combined with a **Digital Elevation Model (DEM)** in **Geographic Information System (GIS) software** and data on the topographic features, landscape morphology and characteristics of the forest roads were collected.

The analysis of the **potential role of logging residues** not only provides useful information to improve the current forest management strategies at the local level, but it is also **extremely relevant** from both a **political** and a **scientific point of view**.

Experimental tests are needed to obtain information on the currently harvested mass of residues and to perform the validation of the results, that up to now is not possible since no measured stand-level data are available.

The **first activity** of the PhD Thesis provides a **significant contribution** to the development of **new tools** merging traditional forest management activities with new challenges posed by climate change mitigation. In particular, the application of methodological approaches developed at the regional and national level using information and data made available at the local level represents an **innovative and useful example of a bottom-up approach** which could be extended also to **other areas**. This is particularly important considering the ongoing debate on the future role of the forest sector to achieve the EU-2050 targets for climate change, and it is also in line with the proposed **"Smart Climate Forestry"** approach, which aims to increase forests' productivity and landowners' incomes by increasing the resilience to climate change and reducing, at the same time, CO_2 and other GHGs concentrations in the atmosphere (e.g., through tax incentives for regeneration with more resilient trees, use of wood instead of more C-intensive materials, C credits and other payments for ecosystem services[8]).

At the same time, however, it is also crucial to point out that, despite in Italy the **stewardship of forest ecosystem services** (e.g., biodiversity conservation, landscape conservation and hydrogeological risk protection) increased in the last decades and fully achieves the EU environmental objectives[9], a problem of the Italian forest sector is the **scarce diffusion of FMPs** (which actually cover only the **19.2%** of the forests), and thus the lack of data at the local scale. This could limit the broader application of the proposed approach. FMPs are essential to ensure the **continuous provision of ecosystem services** over space and time, according to the needs of stakeholders and the national and international Regulations[10]. Therefore, it is essential to urge the public administrations to take appropriate initiatives at both the regional and the national scale to increase the forest area covered by FMPs.

Generally speaking, a **future perspective** for the first activity of the PhD Thesis consists in defining **future management scenarios** which might be aimed at maximizing C retention in the long life-cycle wood products – as required by the recent agreements on climate change – the use of wood for energy purposes, or forest C stock. This allows to **make prediction** and **formulate prescriptions**, promoting an efficient use of the local forestry resources.

In particular, C accounting for the **long life-cycle wood products** can have positive implications for forest management, especially in Italy. Unlike the first commitment period of the Kyoto Protocol (2008-2012), starting from the second commitment period (2013–2020), and in the context of the current **EU regulation 2018/841 for the Land Use, Land Use Change and Forestry sector** (LULUCF), the inclusion of C accounting procedures for wood products is mandatory.

8 Nabuurs G.J., Delacote P., Ellison D., Hanewinkel M., Lindner M., Nesbit M., Ollikainen M., Savaresi A. (2015). A new role for forests and the forest sector in the EU post-2020 climate targets. From Science to Policy 2. European Forest Institute, Joensuu, Finland, pp. 32. https://efi.int/sites/default/files/files/publication-bank/2019/efi_fstp_2_2015.pdf

9 More than 27% of Italian forests are actually included in protected areas; 86.7% of the forests is under limitation of use connected to soil protection and water cycle regulation, and 100% of the forests is under the landscape conservation law. Moreover, the principles of Sustainable and Multifunctional Forest Management and the measures of the Paris Agreements for climate change mitigation are applied at both national, regional and local scales (Marchetti M., Motta R., Pettenella D., Sallustio L., Vacchiano G. (2018). Forests and forest-wood system in Italy: towards a new strategy to address local and global challenges. Forest@ - Journal of Silviculture and Forest Ecology 15: 41-50. https://doi.org/10.3832/efor2796-015).

10 According to Marchetti M., Motta R., Pettenella D., Sallustio L., Vacchiano G. (2018). Forests and forest-wood system in Italy: towards a new strategy to address local and global challenges. Forest@ - Journal of Silviculture and Forest Ecology 15: 41-50. https://doi.org/10.3832/efor2796-015

Nevertheless, it should be underlined that Italian forests which can potentially be used for long-life cycle products are often ageing, abandoned or scarcely managed; therefore, it would be desirable to adopt **sustainable forest management measures** at the local scale. From the point of view of the forest owners, the incomes deriving from forest goods and services can be invested to improve the productivity of the forest itself.
Implementing sustainable forestry measures is, however, influenced by the **scarce availability of specific programming tools and incentives**. In Italy, there is a regime of regulations and a restrictive political system, which controls the produced or marketed forestry resources; moreover, different national and local policies did not allow to carry out a constant flow of raw materials from forests to local communities[11].

Since **forestry mechanization** plays a crucial role in wood procurement, the **second activity** of the PhD Thesis focused on the development of an **innovative approach** to select the most suitable Forestry Machinery Chain (FMC) to adopt for wood collection at the stand level and to compute, at the same time, the economic costs ($€\cdot h^{-1}$; $€\cdot t^{-1}$ DM; €) of the selected chain. To make the selection feasible, a model called **FOREstry MAchinery chain selection (FOREMA v1)** was developed. FOREMA v1 defines the feasible FMC by taking into account **seven technical parameters** that characterized the stand. For each FMC, the sequence of the operations and the types of usable machines are defined. The **economic costs** of the selected FMC are then computed by taking into account all the fixed and the variable costs of each operation. The approach was applied for a Case Study concerning the collection of woodchips from a coppice stand in the Italian Alps for energy generation.

Generally speaking, the described approach can be of practical help for forestry authorities and logging companies, since it can be used to **rationalize the work**, award **public grants/subsidies** and set **transparent operations tariffs**.

The forestry and the operating conditions affect not only the economic costs of the operations, but also their **environmental performances**. This is particularly important for the Alpine Region, where the operations are often performed on steep terrain and over long transport distances. The use of materials, fuels, oil, and lubricants, as well as the emissions of polluting compounds into the atmosphere, water, or soil, always causes impacts on the environment. The simultaneous calculation

[11] Perone A., Di Benedetto S., Vizzarri M., Lasserre B. (2015). Carbon stock in wood products: implications for carbon accounting at national and local scale in Italy. Italian Journal of Forest and Mountain Environments 70(4): 257-272. https://doi.org/10.4129/ifm.2015.4.02

of the economic costs and the environmental performances allows to better define the sustainability of the FMCs.

Therefore, a **future perspective** for this second activity of the PhD Thesis consists in developing an **integrated approach** to select the most feasible FMC for wood collection and to quantify, at the same time, both the economic costs and the environmental performances of the chain.