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

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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. We developed a user-friendly model, based on site-specific primary (measured) data, and we applied it to a dataset of 2019 stands extracted from 45 Forest Management Plans. 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

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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 (GHGs) 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 (HWPs), 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 (VCMs) 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 very 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 forest management plans (FMPs), (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, CC 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" (2011) and the "Carbon Technical Table" (Piedmont Region 2017), respectively. 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 ha^{-1}) of Valle Camonica forest biomass, at the stand level, to support a local VCM. We developed a user-friendly model, based on site-specific primary data, and we applied it 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.

Materials and methods

The model allows the estimation of the TCS (t C 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): (1) SC$_1$—forest structure, (2) SC$_2$—forest function, and (3) SC$_3$—forest typology and variants (Del Favero 2002). 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 (for further details see Supplementary Material).

This one consists of a database where each forest stand (j) represents a record, organized in several fields containing specific input data. For each of the j-stand, the input data required are: (1) starting ($YR_{S(j)}$) and deadline ($YR_{D(j)}$) year of the FMP, (2) location (inside/outside parks or other protective areas), (3) structure, (4) function, (5) typology, (6) area ($A_{(j)}$; ha), (7) growing stock volume ($GSV_{(j)}$; m^3 ha^{-1}) at $YR_{S(j)}$, (8) gross annual increment of GSV ($GAI_{n(j)}$; m^3 ha^{-1} a^{-1}) at $YR_{S(j)}$, and (9) harvesting of GSV over time ($H_{n(j)}$; m^3 ha^{-1} a^{-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 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, so that the gross annual increment associated to each of the j-stand ($GAI^*_{n(j)}$ m^3 ha^{-1} a^{-1}) is calculated as:

$$GAI^*_{n(j)} = k_I \cdot GAI_{n(j)} \tag{1}$$

This coefficient was 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 of the j-stand. In particular, 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 (for further details about k_I definition see Supplementary Material). 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 ha^{-1}) is calculated, for each of the j-stand, through a "gain–loss balance", starting from the GSV of the previous year ($GSV_{n-1(j)}$; m^3 ha^{-1}), adding the gross annual increment as previously defined ($GAI^*_{n(j)}$; m^3 ha^{-1} a^{-1}) and subtracting losses due to harvesting (if any) in the year n ($H_{n(j)}$; m^3 ha^{-1} a^{-1}):

$$GSV_{n(j)} = GSV_{n-1(j)} + GAI^*_{n(j)} - H_{n(j)} \tag{2}$$

To define the TCS (t C ha^{-1}) at the starting year of the simulation, $H_{n(j)}$ values come directly from the FMPs (primary data), while 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 ha^{-1} a^{-1}) is calculated as follows:

$$H_{n(j)} = GAI^*_{n(j)} \cdot k_H \tag{3}$$

The harvesting year (YR_H) is defined by the user in the carbon storage assessment spreadsheet for each of the j-stand.

According to the IPCC Guidelines (IPCC 2006) forest carbon storage should be assessed in: (1) living biomass (aboveground and belowground), (2) dead organic matter (deadwood and litter), and (3) soil. The model estimates the total carbon storage ($TCS_{TB(j)}$; t C ha^{-1}) in (Table 1): (1) aboveground woody biomass ($TCS_{AB(j)}$; t C ha^{-1}), (2) belowground woody biomass ($TCS_{BB(j)}$; t C ha^{-1}), (3) dead

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

Nos.	Name and definition
1	Aboveground woody biomass: over-bark living woody biomass above the soil surface. Stems and branches of all dimensions are included. Foliage is excluded.
2	Belowground woody 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	Dead woody biomass: 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.

woody biomass ($TCS_{DW(j)}$; t C ha^{-1}), and (4) litter ($TCS_{LI(j)}$; t C ha^{-1}).

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, we excluded the soil from our analysis. The TCS is estimated as a function of $GSV_{n(j)}$ (m^3 ha^{-1}) (Federici et al. 2008):

$$TCS_{AB(j)} = GSV_{n(j)} \cdot k_1 \cdot k_2 \cdot k_5 \qquad (4)$$

$$TCS_{BB(j)} = GSV_{n(j)} \cdot k_2 \cdot k_3 \cdot k_6 \qquad (5)$$

$$TCS_{DW(j)} = GSV_{n(j)} \cdot k_1 \cdot k_2 \cdot k_4 \cdot k_7 \qquad (6)$$

where $TCS_{AB(j)}$ is TCS of aboveground woody biomass (t C ha^{-1}); $TCS_{BB(j)}$ is TCS of belowground woody biomass (t C ha^{-1}); $TCS_{DW(j)}$ is TCS of dead woody biomass (t C ha^{-1}); $GSV_{n(j)}$ is growing stock volume of the *j*-stand for the year *n* (m^3 ha^{-1}); k_1 is biomass expansion factor (aboveground woody biomass volume on growing stock volume); k_2 is wood basic density, ratio between wood dry matter and wood fresh volume (t m^{-3} of dry matter); k_3 is root-shoot ratio (belowground woody biomass dry matter on growing stock biomass dry matter); k_4 is dead woody biomass expansion factor (dead woody biomass dry matter on aboveground woody biomass dry matter); k_5 is carbon fraction of aboveground woody biomass dry matter; k_6 is carbon fraction of belowground woody biomass dry matter; k_7 is carbon fraction of dead woody biomass dry matter.

The TCS of litter woody biomass ($TCS_{LI(j)}$; t C ha^{-1}) is estimated by applying linear equations to the TCS of aboveground woody biomass (Federici et al. 2008):

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

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

Rupicolous stands: $TCS_{LI(j)} = \left(-0.0165 \cdot TCS_{AB(j)}\right) + 7.3285$ (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 woody biomass is:

$$TCS_{LB(j)} = TCS_{AB(j)} + TCS_{BB(j)} \qquad (10)$$

The TCS of the dead organic matter is:

$$TCS_{DOM(j)} = TCS_{DW(j)} + TCS_{LI(j)} \qquad (11)$$

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

$$TCS_{TB(j)} = TCS_{LB(j)} + TCS_{DOM(j)}. \qquad (12)$$

Case study

We applied our model to the Valle Camonica District to estimate, for the first time, the TCS related to public forests (Fig. 1). The total forest area of the District is 6.5×10^4 ha, approximately 52% of the total area; 4.2×10^4 ha, approximately 64%, are public (managed through FMPs), whereas the remaining 2.3×10^4 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 (5.1×10^4 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%).

We extracted data related to 2019 forest stands from 45 FMPs collected in the reference database (Cadastral FMPs database; CPA v 2.0) made available by the Operative Unit "Forests and Mountain Remediation" of the Mountain Community. The area of these stands is very heterogeneous, as shown in Table 2.

We did not take into account stands located in the "Legnoli" and "Valle di Scalve" forests because no data were

Fig. 1 Case study area. *Source*: https://www.google.it/maps)

Table 2 Area of the stands extracted from the CPA v 2.0

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

SD standard deviation

made available from the CPA v 2.0. Moreover, we did not consider stands outside the District. 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 v 2.0, we used values based on weighted averages and provided by literature (Del Favero 2002). We estimated $TCS_{DW(j)}$ 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, we considered specific values of k_5, by taking into account the stem of the leading species (Thomas and Martin 2012). If they were not available, we chose general values of $k_5 = 0.508$ for coniferous and $k_5 = 0.477$ for broadleaves stands (Thomas and Martin 2012). We assumed that $k_5 = k_6 = k_7$ (for further details see Supplementary Material).

To define the TCS (t C 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 (no more recent data were made available from the CPA v 2.0). We set the k_I coefficient equal to 1 for each

classification criteria. S_1 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, we chose different harvesting intensity (k_H; % $GAI^*_{n(j)}$) based on the prevailing function of the stands and we considered the following categories:

1. C1—coniferous stands with production function ($A_{C1} = 1.75 \times 10^4$ 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% of $GAI_{n(j)}$, approximately), for all the stands included in this category we 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;

2. C2—coniferous, broadleaves (both coppices and high forests) and mixed forests stands with protection function ($A_{C2} = 1.25 \times 10^4$ 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 (Ducoli 2012). For all the stands included in this category we assumed $k_H = 80\%$ $GAI^*_{n(j)}$;

3. C3—broadleaves and mixed forests stands with production function, stands with recreational function and damaged stands to be recovered ($A_{C3} = 3.56 \times 10^3$ 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 the ones 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 we assumed $k_H = 50\%$ $GAI^*_{n(j)}$;

4. C4—coppices stands with production function ($A_{C4} = 3.19 \times 10^3$ 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 (used for energy purposes in this case) maintaining the growing stock volume constant over time. Therefore, for all the stands included in this category we assumed $k_H = 90\%$ $GAI^*_{n(j)}$

Also for this Scenario, we set the k_I coefficient equal to 1 for each classification criteria. Regarding the harvesting year (YR_H), according to the suggestions of the Mountain Community, for each of the j-stand, we assumed to carry out woody biomass harvesting each year from 2017 to 2029. Moreover, we also assumed that the area of each forest stand does not change over time. We did not take into account S_2 Scenario (SST$_P$, past sustainable) 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, we evaluated the changing in the TCS 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. We assumed to convert 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 we assumed—as a first approximation—that the $GAI_{n(j)}$ was the same of the stands already managed as high forest. Thus, we calculated the ratio between the weighted average $GAI_{n(j)}$ of high forests stands and the weighted average $GAI_{n(j)}$ of coppices stands and we assigned this ratio to the k_I coefficient in the parameters selection spreadsheet. We used the following values of k_I:

- *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).

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

Results and discussion

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 ha^{-1}) was $TCS_F = 76.02$ t C 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 type of management, the TCS of coppices (growing stock volume $GSV_{F1} = 93.42$ m^3 ha^{-1}) was $TCS_{F1} = 53.93$ t C 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 ha^{-1}) was $TCS_{F2} = 79.92$ t C ha^{-1}. Of this, $TCS_{AB\_F2} = 64.24\%$, while $TCS_{BB\_F2} = 14.52\%$. $TCS_{DW\_F2} = 14.90\%$, while $TCS_{LI\_F2} = 6.34\%$ (Fig. 2) (for further details about the absolute values see Supplementary Material).

S$_1$ and S$_3$ scenario assessment

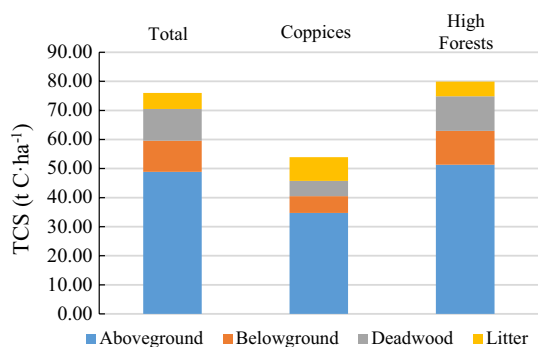Forests should be managed to deliver in a sustainable way an optimal mix of social, environmental (including biodiversity conservation) and economic services. The management options may lead to different outcomes, so that complex trade-offs may emerge (EASAC 2017). At this purpose, forest management 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 the FMPs. 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 $GAI_{AVC1} = 4.47 \pm 2.78$ m^3 ha^{-1} a^{-1}; minimum gross annual increment $GAI_{MINC1} = 0.03$ m^3 ha^{-1} a^{-1}; maximum gross annual increment $GAI_{MAXC1} = 25.30$ m^3 ha^{-1} a^{-1};
- for C2 (coniferous, broadleaves—both coppices and high forests—and mixed forests stands with protection function): $GAI_{AVC2} = 1.73 \pm 1.53$ m^3 ha^{-1} a^{-1}; $GAI_{MINC2} = 0.02$ m^3 ha^{-1} a^{-1}; $GAI_{MAXC2} = 10.35$ m^3 ha^{-1} a^{-1};

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

- for C3 (broadleaves and mixed forests stands with production function, stands with recreational function and damaged stands to be recovered): $GAI_{AVC3} = 2.80 \pm 2.39$ m^3 ha^{-1} a^{-1}; $GAI_{MINC3} = 0.01$ m^3 ha^{-1} a^{-1}; $GAI_{MAXC3} = 15.56$ m^3 ha^{-1} a^{-1};
- for C4 (coppices stands with production function): $GAI_{AVC4} = 2.02 \pm 1.48$ m^3 ha^{-1} a^{-1}; $GAI_{MINC4} = 0.05$ m^3 ha^{-1} a^{-1}; $GAI_{MAXC4} = 13.00$ m^3 ha^{-1} a^{-1}.

Regarding the carbon storage, our results showed that, in 2029 (total growing stock volume $GSV_F = 186.89$ m^3 ha^{-1}) $TCS_F = 78.50$ t C 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 type of management, for coppices (growing stock volume $GSV_{F1} = 98.32$ m^3 ha^{-1}) $TCS_{F1} = 56.27$ t C 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 ha^{-1}) $TCS_{F2} = 82.42$ t C ha^{-1}. Of this, $TCS_{AB\_F2} = 64.32\%$, while $TCS_{BB\_F2} = 14.52\%$. $TCS_{DW\_F2} = 14.90\%$, while $TCS_{LI\_F2} = 6.26\%$ (Fig. 3) (for further details about the absolute values see Supplementary Material).

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, hypothesizing to convert: (1) *F. sylvatica* L. ($A_1 = 3.25 \times 10^2$ ha), (2) *Q. robur* L. and *Q. pubescens* Willd. ($A_2 = 3.87 \times 10^2$ ha), (3) *C. sativa* Mill. ($A_3 = 8.07 \times 10^2$ ha), and (4) *F. ornus* L. and *O. carpinifolia* Scop. ($A_4 = 1.76 \times 10^3$ ha), the TCS can be increased up to 79.49 t C ha^{-1} (total area under conversion = 3.28×10^3 ha). Of this, $TCS_{AB\_F} = 64.56\%$, while $TCS_{BB\_F} = 14.09\%$. $TCS_{DW\_F} = 14.33\%$, while $TCS_{LI\_F} = 7.01\%$ (Fig. 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}) (for further details about the absolute values see Supplementary Material).

As mentioned before, as a first approximation, in the first version of our model, we 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—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 simplified; 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 woody biomass and carbon stocks) can occur. As mentioned before, not having any experimental data to work with, we considered this simplification acceptable within a short period of time and on the large scale considered by our study. In the second version of the model, woody biomass and carbon stocks of aged coppices under conversion will be calculated with more accuracy, by taking into account the temporary
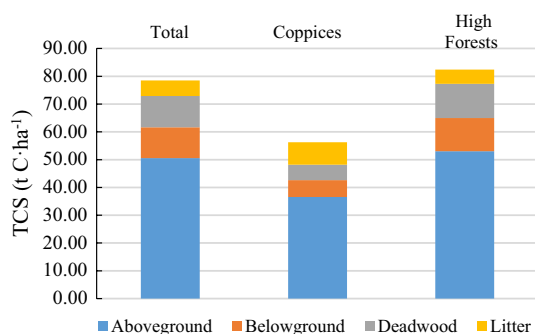

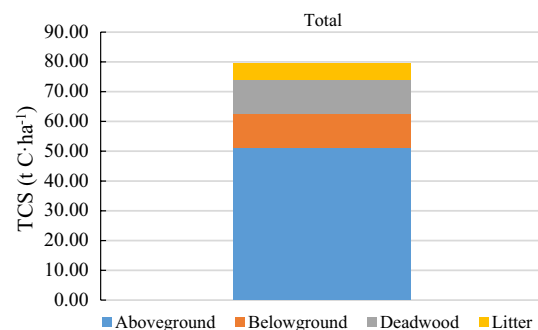**Fig. 3** TCS for the S_1 Scenario (BAU$_F$, future business as usual, year 2029)

Fig. 4 TCS for the S_3 Scenario (SST$_F$, future sustainable, year 2029)

decrease of the gross annual increment. Moreover, we calculated woody biomass and carbon stocks until the deadline year of the most recent FMP (year 2029) without making any assumptions about the possible management practices after that year. In fact, different technical and natural conditions could lead to unreliable results. Because of this, we did not take into account the conversion of abandoned coppices to high forests through natural evolution—which 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 concerns the fact that in all the Scenarios analysed, the gross annual increment was assumed 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 abovementioned simplification is generally applied also in any other FMPs in Italy. In the second version of our 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 and valid for the Lombardy Region.

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.

In this study, we 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 used is currently under improvement, the preliminary information reported by this study can already be used to update the inventory data collected in the FMPs. The carbon storage was calculated not only in the aboveground woody biomass, but also for the belowground biomass, dead wood 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.

References

Affleck DLR (2019) Aboveground biomass equations for the predominant conifer species of the Inland Northwest USA. For Ecol Manag 432:179–188. https://doi.org/10.1016/j.foreco.2018.09.009

Alberdi I, Michalak R, Fischer C, Gasparini P, Brändli UB, Tomter SM, Kuliesis A, Snorrason A, Redmond J, Hernández L, Lanz A, Vidondo B, Stoyanov N, Stoyanova M, Vestman M, Barreiro S, Marin G, Cañellas I, Vidal C (2016) Towards harmonized assessment of European forest availability for wood supply in Europe. For Policy Econ 70:20–29. https://doi.org/10.1016/j.forpol.2016.05.014

Arnoldus M, Bymolt R (2011) Demystifying carbon markets. A guide to developing carbon credit projects. Royal Tropical Institute (KIT), Amsterdam, p 135

Aruga K, Murakami A, Nakahata C, Yamaguchi R, Saito M, Kanetsuki K (2013) A model to estimate available timber and forest biomass and reforestation expenses in a mountainous region in Japan. J For Res 24(2):345–356. https://doi.org/10.1007/s11676-013-0359-4

Bonan GB (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320(5882):1444–1449. https://doi.org/10.1126/science.1155121

Calfapietra C, Barbati A, Perugini L, Ferrari B, Guidolotti G, Quatrini A, Corona P (2015) Carbon mitigation potential of different forest ecosystems under climate change and various managements

in Italy. Ecosyst Heal Sustain 1(8):1–9. https://doi.org/10.1890/ehs15-0023

Carbomark Project (2011) Miglioramento delle politiche verso i mercati locali e volontari del carbonio per la mitigazione del cambiamento climatico [Improvement of policies toward local voluntary carbon markets for climate change mitigation]. http://www.pdc.minambiente.it/en/progetti/carbomark-improvement-policies-toward-local-voluntary-carbon-markets-climate-change. Accessed 07 Feb 2019

de Alegría IM, Molina G, del Río B (2017) Carbon markets: Linking the international emission trading under the united nations framework convention on climate change (UNFCCC) and the European Union emission trading scheme (EU ETS). In: Chen WY, Suzuki T, Lackner M (eds) Handbook of climate change mitigation and adaptation. Springer, Cham, pp 313–339

Del Favero R (2002) I tipi forestali della Lombardia. Inquadramento ecologico per la gestione dei boschi lombardi [Forest typology of Lombardy Region. Ecological framework for the management of Lombardy forests], Cierre, Padova, Italy, p 510

Ducoli A (2012) Modelli di gestione forestale per il Parco dell'Adamello [Models of forest management for Adamello Park]. Tipografia Brenese, Italy, p 274

EASAC (2017) Multi-functionality and sustainability in the European Union's forests. https://easac.eu/fileadmin/PDF_s/reports_statements/Forests/EASAC_Forests_web_complete.pdf. Accessed 23 July 2019

Ekholm T (2016) Optimal forest rotation age under efficient climate change mitigation. For Policy Econ 62:62–68. https://doi.org/10.1016/j.forpol.2015.10.007

Eriksson E, Gillespie AR, Gustavsson L, Langvall O, Olsson M, Sathre R, Stendahl J (2007) Integrated carbon analysis of forest management practices and wood substitution. Can J For Res 37(3):671–681. https://doi.org/10.1139/x06-257

Federici S, Vitullo M, Tulipano S, De Lauretis R, Seufert G (2008) An approach to estimate carbon stocks change in forest carbon pools under the UNFCCC: The Italian case. IForest Biogeosci 1:86–95. https://doi.org/10.3832/ifor0457-0010086

Gorte RW, Ramseur JL (2010) Forest carbon markets: potential and drawbacks. https://fas.org/sgp/crs/misc/RL34560.pdf. Accessed 17 Dec 2018

Grassi G, Pilli R, House J, Federici S, Kurz WA (2018) Science-based approach for credible accounting of mitigation in managed forests. Carbon Balance Manag 13(1):8. https://doi.org/10.1186/s13021-018-0096-2

Gren IM, Zeleke AA (2016) Policy design for forest carbon sequestration: a review of the literature. For Policy Econ 70:128–136. https://doi.org/10.1016/j.forpol.2016.06.008

Harmon ME, Krankina ON, Yatskov M, Matthew E (2001) Predicting broad-scale carbon stock of woody detritus from plot-level data. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, pp 533–552

Hoberg G, Peterson St-Laurent G, Schittecatte G, Dymond CC (2016) Forest carbon mitigation policy: a policy gap analysis for British Columbia. For Policy Econ 69:73–82. https://doi.org/10.1016/j.forpol.2016.05.005

IPPC (2006) 2006 IPCC guidelines for national greenhouse gas inventories, agriculture, forestry, and other land use. Chapter 2, generic methodologies applicable to multiple land-use categories, vol 4. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf. Accessed 17 sep 2018

Jandl R, Bauhus J, Bolte A, Schindlbacher A, Schüler S (2015) Effect of climate-adapted forest management on carbon pools and greenhouse gas emissions. Curr For Rep 1(1):1–7. https://doi.org/10.1007/s40725-015-0006-8

Kollmuss A, Zink H, Polycarp C (2008) Making sense of the voluntary carbon market: a comparison of carbon offset standards. https://mediamanager.sei.org/documents/Publications/SEI-Report-WWF-ComparisonCarbonOffset-08.pdf. Accessed 20 Dec 2018

Masera OR, Garza-Caligaris JF, Kanninen M, Karjalainen T, Liski J, Nabuurs GJ, Pussinen A, De Jong BHJ, Mohren GMJ (2003) Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX vol 2 approach. Ecol Model 164(2–3):177–199. https://doi.org/10.1016/S0304-3800(02)00419-2

Merger E, Pistorius T (2011) Effectiveness and legitimacy of forest carbon standards in the OTC voluntary carbon market. Carbon Balance Manag. https://doi.org/10.1186/1750-0680-6-4

Nabuurs GJ, Thürig E, Heidema N, Armolaitis K, Biber P, Cienciala E, Kaufmann E, Mäkipää R, Nilsen P, Petritsch R, Pristova T, Rock J, Schelhaas MJ, Sievanen R, Somogyi Z, Vallet P (2008) Hotspots of the European forests carbon cycle. For Ecol Manag 256(3):194–200. https://doi.org/10.1016/j.foreco.2008.04.009

Nabuurs GJ, Arets EJMM, Schelhaas MJ (2018) Understanding the implications of the EU-LULUCF regulation for the wood supply from EU forests to the EU. Carbon Balance Manag 13:18. https://doi.org/10.1186/s13021-018-0107-3

Noormets A, Epron D, Domec JC, McNulty SG, Fox T, Sun G, King JS (2015) Effects of forest management on productivity and carbon sequestration: a review and hypothesis. For Ecol Manag 355:124–140. https://doi.org/10.1016/j.foreco.2015.05.019

Piedmont Region (2017) Disposizioni per lo sviluppo del mercato volontario dei crediti di carbonio da selvicoltura nella Regione Piemonte [Guidelines for the development of the voluntary carbon credit market from forest management in the Piedmont Region]. http://www.regione.piemonte.it/governo/bollettino/abbonati/2017/06/attach/dgr_04638_370_06022017.pdf. Accessed 07 Feb 2019

Raufer R, Coussy P, Freeman C, Iyer S (2017) Emissions trading. In: Chen WY, Suzuki T, Lackner M (eds) Handbook of climate change mitigation and adaptation. Springer, Cham, pp 257–312

Ruiz-Peinado R, Bravo-Oviedo A, López-Senespleda E, Bravo-Oviedo F, del Río M (2017) Forest management and carbon sequestration in the Mediterranean region: a review. For Syst. https://doi.org/10.5424/fs/2017262-11205

Rutherford DJ, Weber ET (2017) Ethics and environmental policy. In: Chen WY, Suzuki T, Lackner M (eds) Handbook of climate change mitigation and adaptation. Springer, Cham, pp 127–165

Thomas SC, Martin AR (2012) Carbon content of tree tissues: a synthesis. Forests 3(2):332–352. https://doi.org/10.3390/f3020332

UNFCCC (1992) The United Nations framework convention on climate change. https://unfccc.int/resource/docs/convkp/conveng.pdf. Accessed 12 Sep 2018

Vacchiano G, Berretti R, Romano R, Motta R (2018) Voluntary carbon credits from improved forest management: policy guidelines and case study. iFor Biogeosci For 11(1):1–10. https://doi.org/10.3832/ifor2431-010

Zeng W, Fu L, Xu M, Wang X, Chen Z, Yao S (2018) Developing individual tree-based models for estimating aboveground biomass of five key coniferous species in China. J For Res 29(5):1251–1261. https://doi.org/10.1007/s11676-017-0538-9