Carbon stock estimation in an unmanaged old-growth forest: a case study from a broad-leaf deciduous forest in the Northwest of Italy

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SUMMARY

The aim of the study was to evaluate the carbon storage capability of an unmanaged old-growth deciduous forest developing inside a Natural Reserve. Our research aims to emphasize how the conservative management, by determining the actual structure and species composition, resulted in a high carbon storage capability. The results highlight that the forest stores a large carbon amount (C_{Tot} = 418 Mg C ha^{-1}) with the greater pool in the aboveground biomass and in the soil (42%). In particular, among the most abundant species, *Populus* spp. and *Quercus robur* are the major carbon sink of the forest, accounting for 31% and 63% of the forest aboveground biomass. In addition, the total economic benefits from carbon storage of the forest of 11 209 $ ha^{-1} was estimated. Thus, preserving this type of forest structure and tree species composition can ensure in the future the same forest contribution to the local carbon stock.

Keywords: aboveground biomass; carbon storage; old-growth forest; unmanaged forest

Estimation de stockage de carbone dans une vieilles forêt: êtude de cas sur une forêt tempérée décidue au nord-ouest de l'Italie

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L' objectif de l'étude était d'évaluer la capacité de sequestration du carbone par une forêt primaire décidue, se développant à l'intérier d'une Réserve Naturelle. Notre recherche vise à mettre en évidence comment une gestion conservatrice, en déterminant la structure de la forêt et les espèces composantes, a eu comme résultat une haute capacité de stockage du carbone. Les résultats ont montré que la forêt retient une grande quantité de carbone dans biomasse èpigée (42%). En particulier, entre les espèces les plus abondantes, *Populus* spp. et *Quercus robur*, représentent le puits de carbone principal, qui compte pour 31% et 63%, respectivement, de la biomasse èpigée. Les bénéfices économiques totales d'une telle forêt, par rapport à sa capacité d'absorption du carbone, ont été estimés à 11 209 $ ha^{-1}. En préservant ce type de structure forestière ainsi que sa compostion d'espèces, dans le futur cela contribuera de la même manière au stockage du carbon sur le plan local.

Estimación de almacenamiento de carbono de un bosque de edad madura no manejados: un estudio de caso de un bosque caducifolio en el noreste de Italia

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El objetivo del studio fue evaluar la capacidad de almacenamiento de carbono de un bosque caducifolio no manejados de edad madura que se desarrolla en una Reserva Natural. Nuestra investigación tiene como objetivo enfatizar cómo el tratamiento conservador, mediante la determinación de la estructura actual y la composición del las species, dio como resultado una capacidad de almacenamiento de alto contenido de carbono (C_{Tot} = 418 Mg C ha^{-1}), el pool con el mayor contenido de carbono resultó la biomasa area y el suelo (42%). Las especies con el mayor contenido de carbono en la biomasa del fuste fueron *Populus* spp. y *Quercus robur.* Además, se estimó beneficio económico totales de almacenamiento de carbono del bosque de 11 209 $ ha^{-1}. Así, la preservación de este tipo de estructura del bosque y la composición de especies arbóreas puede asegurar en el futuro la misma contribución de el bosque a las reservas de carbono local.

INTRODUCTION

Forest ecosystems are important components of the global carbon cycle. The Kyoto Protocol (UNFCCC 1997) recognized the role of forests in carbon sequestration to mitigate climate change and encouraged forestation projects and strategies for adapted forest management activities (Brown *et al.* 2002). The Inter-governmental Panel on Climate Change highlights that the forestry sector has one of the greatest potential to reduce atmospheric CO_2 at a reasonable cost in the next decades, compared to all other mitigation activities (IPCC 2007). In fact, forests contribute to climate change mitigation by removing atmospheric carbon dioxide and storing it in different carbon pools (i.e., biomass, soil, dead organic matter, litter) accounting for 77–82% of the total carbon stocked by the terrestrial vegetation (Garcia-Gonzalo *et al*. 2007). Carbon is accumulated in forests through biomass, dead organic matter, litter and soil while it is released throughout respiration and decomposition (Del Río *et al.* 2008). Forests switch between being a source or a sink of carbon, depending on the succession stage, forest type, disturbance and management activities (Masera *et al.* 2003). The capacity of forests to act as a carbon sink generally decreases with age as respiration begins equal or exceeds net photosynthesis (Odum 1969). However, little evidence exists that this hypothesis holds true for unmanaged forests covering a wide range of age classes due to natural regeneration and canopy structure (Knohl *et al.* 2003). Forest management has an important impact on carbon balance (McGrath *et al*. 2015) and human activities have several direct and indirect influences on forest ecosystems and thus, on carbon sequestration potential (Nabuurs and Schelhaas 2002). In Europe, the total area covered by forests has increased by 25% since 1950 (Fuchs *et al.* 2013) resulting in a 44% forested area of ecological, political and economic importance (Gallaun *et al.* 2010). In particular, the European forests absorb about 10% of the European CO_2 emission (Cameron *et al.* 2013). There has been a long history of forest exploitation and management in Europe. Thus, the conservation of mature forests is important for the long-term permanence of forest C sinks (Carey *et al.* 2001). In such context, a forested area of 30 million of ha in Europe has been protected with the main objective to conserve the biodiversity and landscape as triggered by the EU's biodiversity policy (Forest Europe *et al.* 2011). In particular, old-growth forests provide a large number of ecosystems services such as biodiversity conservation, carbon reservoir and the opportunity for studying ecological process in undisturbed conditions (Wirth *et al.* 2009). Thus, due to the importance of the forest role in carbon stored and biodiversity conservation, the interest in forested areas has increased in recent years (Parviainen 2005, Kallio *et al*. 2008, Hein 2011). Moreover, carbon stock estimation and knowledges about its distribution in the different compartments (i.e. aboveground, belowground, deadwood, litter and soil) is essential to evaluate the quantity of carbon that is potentially emitted to the atmosphere when natural or human-induced disturbance occurs (Fonseca *et al*. 2012). In this context, the main objective of our research was to evaluate the amount of the total carbon stocked and its distribution in its compartments in a unmanaged old-growth broadleaf deciduous forest developed inside the Riserva Integrale Bosco Siro Negri (Northwest of Italy). We analyzed the effect of this type of management on the forest carbon stock also considering the plant species regeneration inside the forest and in the forest boundary.

MATERIALS AND METHODS

Study area

The study was carried out in an old-growth deciduous forest developing inside the Riserva Integrale Bosco Siro Negri (45°12′39″N; 09°03′26″E, 74 m a. s. l) in Italy, in the period May–July 2015. The studied forest is one of the few relicts of the original forest which in the past covered the alluvional valley along the Ticino river and where no logging has been carried out since the establishment of the Reserve in 1970 (Sartori 1984, Motta *et al.* 2009, Castagneri *et. al*. 2013). The Reserve is a SIC (IT 2080014 'Bosco Siro Negri e Moriano'). The structure of the forest is that of a typical old-growth closed forest. It is characterized by a mosaic of different sized canopy gaps, decaying logs on the forest floor and dead standing trees. The tree layer has a mean height of 20 m and it is dominated by *Quercus robur* L., *Acer campestre* L., *Robinia pseudoacacia* L., *Ulmus minor* Mill., *Populus nigra* L. and *Populus alba* L. Many trees are more than 100-years old (Castagneri *et al.* 2013). The dominated tree layer is characterized by younger individuals of the dominant species and also by *Corylus avellana* L., *Prunus padus* L. and herbaceous species. The forest tree density is 237 ± 100 stems ha^{-1}, the total basal area 74.5 ± 24.6 m^2 ha^{-1} and the Leaf Area Index (LAI) 4.5 ± 0.3 (Catoni *et al*. 2015a). The soil nitrogen content (N) is 0.16 ± 0.01%, the carbon/ nitrogen content ratio (C/N) 17 ± 1 and the organic matter (SOM) of 4.4 ± 0.1% (Catoni *et al*. 2015b).

The climate of the area is characterized by a total annual rainfall of 654 mm most of it falling in autumn and winter. The mean minimum air temperature (T_{min}) of the coldest month (January) is –0.2 ± 1.8°C, the mean maximum air temperature (T_{max}) of the hottest month (July) 30.1 ± 1.3°C and the mean annual temperature (T_m) 13.7 ± 8.2 °C. Floods occurred sporadically every 5–10 years during the last 40 years, with water levels up to 1.50 m height in the forest during exceptional events (Motta *et al*. 2009, Castagneri *et al.* 2013). On average, groundwater level is around –4.50 m in winter reaching –3.50 m in summer due to irrigation in the surrounding area. During the study period, total rainfall was 257 mm, T_m 21.0 ± 4.9°C and T_{max} (July) 32.8 ± 2.5°C (Lombardia Regional Agency for Environmental Protection, Meteorological Station of Pavia, Ponte Ticino SS35, data for the period 2002–2014 and May–July 2015).

Forest measurements

The forest extension was measured by the QGIS (Geographic Information System) which is a tool for the digital landscape exploration proving the necessary functions for spatial data collection, management, analysis and representation.

Forest measurements were carried out on 10 randomly sample areas (500 m^2 each, according to Gallaun *et al*. 2010). The following species were considered: *A. campetre*, *C. avellana*, *Crateagus monogyna* L., *P. alba*, *P. nigra*, *P. padus*, *Q. robur*, *R. pseudoacacia* and *U. minor*. Trees with a diameter greater than 5 cm (Tabacchi *et al*. 2011) and in a good condition (i.e. percentage of branch dieback in crown between 1% and 10%, according to Nowak *et al*. (2002) were considered. In particular, tree height (H) was measured by clinometers and diameter at the breast height (dbh) by callipers. The density of the considered species (plants ha^{-1}) was determined in the whole area of the Reserve.

Plant regeneration

Plant regeneration was measured in 50 randomly selected plots (25 m^2 each) distributed inside the forest and in the forest boundary (parallel at the forest, at a distance of 5 m from the forest border). Saplings were defined as woody plants between 0.5 and 3 m tall, according to Hall and Swaine (1976).

Microclimate

Microclimate was measured in June, in the selected plots inside the forest (n = 10), in the forest boundary (n = 10 plots) and in the open (n = 10 plots in clearing outside the forest), from 12:00 p.m. to 04:00 p.m. in 4 days with comparable weather conditions and without clouds (the same plots used for plant regeneration were used). The photon flux density (PFD) was measured by a quantum radiometer (LI-189 LI-COR, USA) with a quantum sensor LI-190SA. The photon flux density was measured at soil level below the vegetation both inside the forest ($PFD\%_I$) and at the forest boundary ($PFD_{\%B}$) with the following formula:

$$PFD_{\%} = PFD_b/PFD_o$$

where PFD_b was the photon flux density below the vegetation and PFD_o was photon flux density measured outside the forest. Measurements of irradiance in red light (R, 660 nm), far-red light (FR, 730 nm) and blue spectral bands were carried out with a photometer IL 150 (International Light, U.S.A.) in each of the considered plots. Moreover, the ratio R/FR was calculated in order to quantify the quality of solar radiation (Mitchell and Woodward 1988).

Forest biomass and carbon storage

The aboveground biomass (AB_S) of each species was obtained by allometric equations (Zianis *et al.* 2005, Tabacchi *et al*. 2011) using dbh and H for each species. The forest aboveground biomass (AB_F) was obtained by summing the product of AB_S and the related plant density for each of the considered species. The forest belowground biomass (BB_F) was obtained by multiplying AB_F and the root/shoot ratio, according to Vitullo *et al.* (2007) and Federici *et al*. (2008). The forest dead wood biomass (DB_F) was calculated by multiplying AB_F by the Dead Factor Conversion (DFC = 0.14, IPCC 2003), according to Vitullo *et al.* (2007) and Federici *et al.* (2008).

The carbon storage in the aboveground (C_A), belowground (C_B) and deadwood (C_D) biomasses was calculated by multiplying AB_F, BB_F and DB_F by 0.5, respectively (IPCC 2003). Carbon storage in the litter (C_L) and in the soil (C_S) was estimated using a linear correlation where C_L and C_S were the dependent variables and AB_F the independent variable, according to Federici *et al*. (2008).

In particular, the relation between litter and aboveground C ha^{-1} was expressed by the following equation:

$$y = -0.0299AB_F + 9.3665$$

and the relation between the soil and the aboveground C ha^{-1} was expressed by the following equation:

$$y = 0.9843AB_F + 5.0746$$

The total forest carbon storage (C_{Tot}, Mg C ha^{-1}) was obtained by summing $C_{A,}$ C_B, C_D, C_L and C_S.

Statistical analysis

All statistical tests were performed using a statistical software package (PAST, Version 3.10). Differences in the considered traits were determined by the analysis of variance (ANOVA) and the Tukey test for multiple comparisons. Kolmogorov–Smirnov and Levene tests were used to verify the assumption of normality and homogeneity of variances, respectively. Values are reported as mean ± standard error (S.E.).

RESULTS

Forest structure and microclimate

Among the considered species, *U. minor* had the highest density (45 plants ha^{-1}), followed by *Q. robur* (40 plants ha^{-1}), *R. pseudoacacia* and *C. monogyna* (38 plants ha^{-1}), *A. campestre* (19 plants ha^{-1}), *P. nigra* (17 plants ha^{-1}), *C. avellana* (15 plants ha^{-1}), *P.padus* and *P. alba* (9 plants ha^{-1}).

Plant traits are shown in table 1. *P. nigra* had the highest height and diameter at the breast height (38 ± 8 m and 106 ± 24 cm, respectively) and *C. avellana* the lowest (5 ± 1 m and 10 ± 4 cm, respectively). The diameter distribution of each of the considered species is shown in figure 1.

The ratio of red to far-red spectral bands (R/FR) were 0.5 ± 0.1, 0.78 ± 0.2 and 1.2 ± 0.2, inside the forest, in the forest boundary and in the open, respectively. Moreover, the photon flux density at soil level inside the forest ($PFD_{\%I}$) and in the forest boundary ($PFD_{\%B}$) were 0.77 ± 0.12% and 1.54 ± 0.12%, respectively.

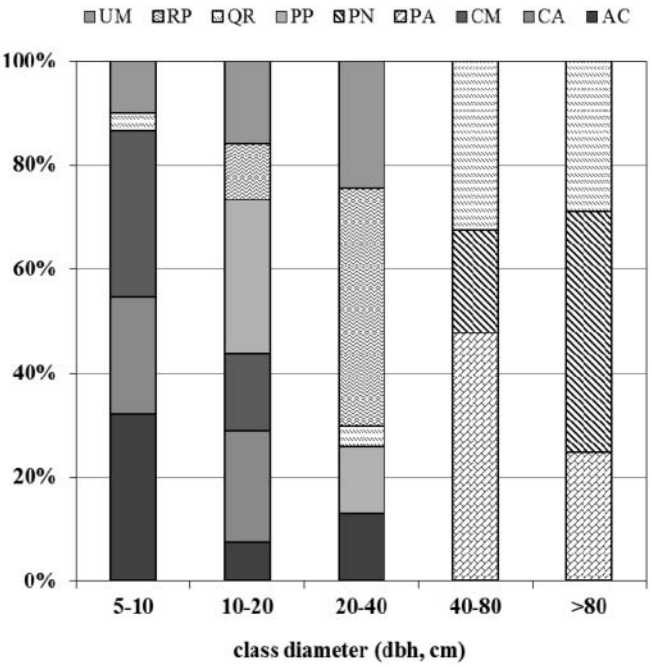
Plant regeneration

Plant regeneration inside the forest and in the forest boundary is shown in table 2. In particular, inside the forest *P. padus*

TABLE 1 *Structural traits of the considered species; H – plant height, dbh – diameter at breast height. Mean values ± S.E. are shown (n = 100)*

	H m	dbh cm
Acer campestre	10 ± 5	14 ± 5
Corylus avellana	5 ± 2	10 ± 4
Crataegus monogyna	6 ± 2	11 ± 4
Popolus alba	32 ± 4	67 ± 19
Popolus nigra	38 ± 8	106 ± 24
Prunus padus	11 ± 8	16 ± 7
Quercus robur	31 ± 8	73 ± 22
Robinia pseudoacacia	18 ± 6	25 ± 8
Ulmus minor	12 ± 4	17 ± 7

FIGURE 1 *Presence in percentage of each of the considered species in the five class of diameter at breast height. AC = Acer campestre, CA = Corylus avellana, CM = Crateagus monogyna, PA= Populus alba, PN = Populus nigra, PP = Prunus padus, QR = Quercus robur, RP = Robinia pseudo-acacia, UM = Ulmus minor*



showed the highest density (3 000 ± 1 000 saplings ha^{-1}) and *C. monogyna* (744 ± 179 saplings ha^{-1}) the lowest. In the forest boundary, *R. pseudocacia* had the largest density (1 504 ± 262 saplings ha^{-1}) and *P. padus* (18 ± 8 saplings ha^{-1}) the lowest.

Forest carbon storage

The forest aboveground (AB_F), belowground (BB_F), and deadwood (DB_F) biomasses were 348 Mg ha^{-1}, 80 Mg ha^{-1} and 49 Mg ha^{-1}, respectively. The species aboveground biomass contribution to the forest aboveground biomass for each of the considered species is shown in table 3.

The total forest carbon storage (C_{Tot}) was 418 Mg C ha^{-1} to which carbon storage in above-ground (C_A) and in soil (C_S) gave the same contribution (42% each), carbon storage in belowground contributed for 10%, in deadwood for 6% and in litter for 1% (Figure 2).

TABLE 2 *Plant regeneration (saplings ha^{-1}) in the forest interior and in the forest boundary. Mean ± S.E. are shown (n = 50)*

	Saplings ha^{-1}	
	Forest interior	***Forest boundary***
A. campestre	1 976 ± 619	300 ± 58
C. avellana	2 200 ± 653	50 ± 10
C. monogyna	744 ± 179	600 ± 173
P. padus	3 000 ± 1000	18 ± 8
Q. robur		109 ± 42
R. pseudoacacia		1 504 ± 262
U. minor	2 322 ± 985	116 ± 55

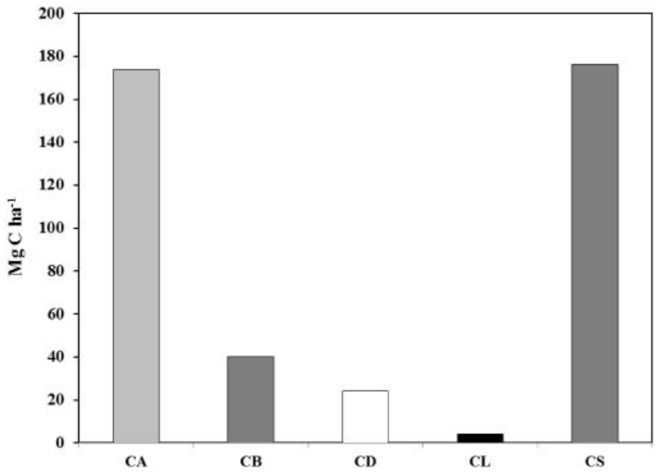
TABLE 3 *Proportion in percentage of the species above-ground to the forest above-ground biomass ($AB_S/AB_{F\%}$) for each of the considered species*

	$AB_S/AB_{F\,(\%)}$
Acer campestre	0.31
Corylus avellana	0.08
Crataegus monogyna	0.23
Popolus alba	4.77
Popolus nigra	26.8
Prunus padus	0.17
Quercus robur	63.0
Robinia pseudoacacia	3.45
Ulmus minor	1.10

DISCUSSION

Carbon stock is associated with plant biomass which, in turn, depends on different factors such as forest management, climate and soil type (van Kooten *et al.* 2004). Moreover, the structure and the species composition contribute to the forest carbon stock. The current tree species composition and structure of the forest under study are the result of the conservative management carried out from the establishment of the Reserve resulting in a high tree density (237 ± 100 stems ha^{-1}) and LAI (4.5 ± 0.3; Catoni *et al.* 2015a), in the range of

FIGURE 2 *Carbon stored for each of the considered forest compartments: C_A = carbon stored in the above-ground biomass; C_B = carbon stored in the below-ground biomass; C_D = carbon stored in deadwood; C_L = carbon stored in the litter; C_S = carbon stored in the soil*



broadleaf deciduous forests in Italy (Gratani and Crescente 2000). The high tree density determines a high light extinction at soil level (i.e. $PFD_{\%I}$ = 0.77 ± 0.12% and R/FR = 0.5 ± 0.1), which is in the range of the typical close canopy forests (0.5–5%; Chazdon and Percy 1991). This result is related to the dominant tree layer largely constituted by *Q. robur*, *P. nigra* and *P. alba* (height = 34 ± 4 m, mean value). The light amount in the forest understory is considered a crucial factor driving many processes such as understory tree regeneration, seedling survival (Kozlowski *et al.* 1991, Lieffers *et al*. 1999), growth (Page *et al.* 2001) and biomass allocation (Messier and Nikinmaa 2000). Thus, the assessment of available light in forest understory is important for a better understanding of a wide range of different processes (Sonohat *et al.* 2004). In this case, the low light in the forest understory determines a low regeneration of the dominant species. In fact, *Q. robur* and *Populus* spp. require sufficient light penetration and large opening for regeneration (Humphrey *et al.* 2002, Motta *et al.* 2009). In particular, regeneration of *Q. robur* (one of the most important European oak species) has been considered a concern in temperate forests because of the extreme scarcity of established saplings and young trees (Kelly 2002). This is due to competition with other species (i.e. shading and root competition) (Shaw 1974), mechanical smothering (Humphrey and Swaine 1997) and the presence of inhibitory substances by field species (Jarvis 1964). In the forest understory there are also few sapling of *R. pseudoacaia*, a typical shade-intolerant specie (Motta *et al.* 2009, Catoni *et al*. 2015a). This result highlights that the conservative management carried out in the Reserve has contributed to maintain under control the spread of this highly invasive species. On the contrary, *C. avellana*, *U. minor*, *A. campestre* (shade-tolerant species) and other broadleaves (*C. monogyna* and *P. padus*) can successfully regenerate at the low light intensity inside the forest and in the gaps (Motta *et al.* 2009) as confirmed by the large saplings density (2 049 ± 368 saplings ha^{-1}, mean value).

The environmental conditions at forest boundaries are intermediate between those in clearings and those inside the forest resulting in a $PFD_{\%B}$ of 1.54 ± 0.12% and a 56% higher ratio of red to far-red light than the forest interior. Accordingly, the species composition in the forest boundary is characterized mainly by shade-intolerant species, in accordance with the results of Chen *et al*. (1992) for temperate-forests. In fact, our results show the largest sapling density for *R. pseudoacacia* (1 504 ± 262 saplings ha^{-1}) and a relatively high sapling number of *Q. robur* (109 ± 42 saplings ha^{-1}) in the forest boundary rather than inside the forest. Otherwise, there are few saplings for the typical shade-tolerant species, i.e. 50 ± 10, 300 ± 58 and 116 ± 55 saplings ha^{-1}, for *C. avellana*, *A. campestre* and *U. minor*, respectively. The different plant regeneration patter in the forest boundary in respect to the interior forest could be seen as the potential forest dynamic if management activities are undertaken. Several type of management, particularly thinning, can modify light solar transmission, which in turn can modify tree growth and development along with other processes such as those involved in plant diversity. Thus, the trees species currently present in the Reserve by fixing CO_2 *via* photosynthesis and storing the carbon in excess as biomass (Nowak *et al*. 2002) determine a total forest above-ground of 348 Mg ha^{-1}, 64% higher than the mean value shown by Saugier *et al.* (2001) for the temperate forests. Among the considered species, *Populus* spp. and *Q. robur* show the higher contribute to the forest aboveground biomass (by 31% and 63%, respectively). The capacity of the species to sequester CO_2 and then to act as carbon sinks depends on their physiology, growth rate, plant structure and coverage (Nowak *et al.* 2002). In this case, these species are characterized by higher photosynthetic rates (Catoni *et al.* 2015a) and AB_S values (3 707 and 5 547 Kg, respectively). In particular, the larger diameter at breast height (87 ± 20 cm and 73 ± 22 cm, respectively) highlights that the diameter is the main driver of the biomass accumulation and, in turn, of the species carbon stocked capacity. On the contrary, *R. pseudoacacia* despite a relatively higher plant density (38 plants ha^{-1}) and a higher photosynthetic rates (Catoni *et al.* 2015a) contributes by 3% to the forest aboveground biomass. This result can be justified by its high growth rate (Mohan *et al.* 2007), due to the negative correlation between relative growth rate and the increased partitioning into non-photosynthetic tissue, as suggested by Shipley and Peters (1990) and resulting in a lower AB_S (319 Kg). The other species (*A. campestre*, *C. avellana*, *C. monogyna*, *U. minor*, *P. padus*, tree density = 25 ± 15 tree ha^{-1}, mean value) contribute less than 2% to AB_F due to their lower AB_S (45 ± 12 Kg, mean value) and diameter at breast height (14 ± 1 cm, mean value).

The carbon stocked in the above-ground biomass (C_A = 174 Mg C ha^{-1}) represents the 42% of the total carbon storage by the forest, which is in the range of temperate forests (147–377 Mt C ha^{-1}) with comparable climatic conditions (Keith *et al.* 2009). Moreover, the carbon stocked by the studied forest is more than 100% higher than that of the Italian Parks (Marchetti *et al.* 2015) confirming that old unmanaged forests can sequester large C amounts.

In addition, our results highlight an equivalent contribution from the soil carbon pool (by 42%), in accordance with the results of Nabuurs *et al*. (2003) for European forests, indicating a significant sink strength of soils. The turnover of soil organic matter depends on soil composition and climate (Jandl *et al.* 2007) and the larger proportion in soils of temperate forests compared to soils in tropical forests is related to a slower decomposition rates (Gorte 2009). Another aspect which should be considered is the species composition (Jandl *et al.* 2007), tree density and root characteristic (i.e. shallow *vs* deep roots). In particular, the rooting depth is relevant for C because root growth is a most effective way of introducing C into the soil (Vesterdal *et al.* 2002). *Populus* spp. and *Q. robur* largely contribute to the soil C pool for the studied forest due to their well-developed root systems (Wong *et al.* 1985, Rosengren *et al*. 2006). The others compartment belowground, deadwood and litter account for 10%, 6% and 1% to C_{Tot}, respectively. In particular, deadwood is a structural and functional element in a forest ecosystem and unmanaged forests typically have more deadwood compared to managed forest (Vandekerkhove *et al*. 2009) providing a resource for plant, animal and fungi. Moreover, the quantity and quality of deadwood provide information on mortality processes and disturbance regime (Castagneri *et al.* 2010) suggesting the degree of forest naturalness and indicating the nearness to the old-growth stage (Winter *et al.* 2010). In the considered forest, a natural disturbance results in the individual-tree death or in small-scale disturbances mainly caused by wind, insects and fungi. The absence of anthropogenic stumps (i.e. a proxy variable of human impact) confirms the high degree of naturalness. Despite litter shows the minor contribution to $C_{Tot,}$ among the five compartments, it results an important component of the carbon biogeochemical cycle (Zhang *et al.* 2007) being the interface between vegetation and soil (Fonseca *et al.* 2012). The litter layer is, in fact, an important pool of nutrients and organic material and its quantity and quality determines the decomposition rate, which in turn defines the availability and mobility of essential elements influencing the functional processes in the forest ecosystems (Walle *et al.* 2001).

On the whole, the considered forest at an ‘advanced’ stage of development stores a large C amount ($C_{Tot} = 418$ Mg C ha^{-1}) with the greater pool in the aboveground biomass and in the soil. Management providing the conservation of carbon stocks in a forest meets with the major climate change mitigation strategies under UNFCCC (United Nations Framework Convention on Climate Change) and assuming a monetary value for stored CO_2 of 0.00334 \$/lb (i.e. 0.00736 \$/kg) (Peper *et al.* 2007) the total economic benefits of carbon storage in this forest amounts to 11 209 \$ ha^{-1}.

In conclusion, this study highlights that the conservative management carried out in this forest can ensure the maintenance of the actual carbon stocked. Thus, our results are an incentive to persist with the conservative management, carried out since the establishment of the Reserve. In fact, considering the plant regeneration potential in the forest boundary compared to the forest interior, it is important to maintain this type of management in the future since creating gaps could allow a greater regeneration of *R. pseudoacacia* over *Q. robur* and *Populus* spp. (i.e. the major carbon sink). Therefore, preserving this type of forest structure and tree species composition can ensure in the future the same forest contribution to the local carbon stock.

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