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CARBON STOCK EVALUATION FROM TOPSOIL OF FOREST STANDS IN NE ITALY

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Gas emissions from anthropic activities, particularly CO2, are responsible for global warming. Soil is a major carbon sink on a planetary level, thereby contributing to mitigate greenhouse effect. In the present work, the objectives were: 1) to evaluate the topsoil carbon stock of different forest stands in NE Italy, and 2) to outline the relationships among humus forms, soil organic matter dynamics, and actual carbon stock under different vegetation coverage, with reference to climate change. Five forest stands and the related topsoils, were selected in the Dolomites area. The humus forms were examined in the field and samples were carried to the lab for further physical-chemical analyses. The carbon stock for each soil was calculated by means of pedotransfer functions. The less developed humus forms, as the Dysmull and the Hemimoder, presented the highest carbon storage capacity (168 t/y and 129 t/y), followed by Lithoamphimus (123 t/y) and Eu-amphimus (96 t/y), and by Oligomull (86 t/y). Organic horizons proved to recover 36% of the total carbon stocked along the soil profile, and this points to humus layers as a fundamental tool in carbon stock evaluation. Positive correlations between elevation, humus forms and soil carbon pools were found.

KEY WORDS: humus forms, forest stands, SOC, pedotransfer functions, carbon stock

INTRODUCTION

Soils represent one of the most important carbon sink on a global scale, and play a key role in global C cycle, which in turn is one of the key processes governing climate change (Penne et al. 2010). According to Batjes (1996), the amount of organic carbon sequestered by the soil (SOC) is larger than the pool of both biosphere (610Pg C) and atmosphere (750 Pg C), totaling ca 1500 Pg C, approximately one-quarter of the total amount produced by human activities. Forest soils are particularly enriched in organic matter (SOM) with respect to agricultural soils, and represent a fundamental sink for atmospheric CO_2 sequestration; however, they can be also a source of greenhouse gases, as CO_2 and CH_4, depending on the processes which govern SOM accumulation and stabilization, or losses (Zimmermann et al. 2007; Lal 2009). Yet, changes in the amount of SOM pools and in its turnover rate may potentially alter the atmospheric CO_2 concentration, and consequently the global climate (IPCC 2001). The capacity of soils to accumulate and stabilize organic carbon has received great attention in recent years (Lützow et al. 2006, 2008; Spielvogel

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et al. 2009; Gruneberg et al. 2010; Llorente et al. 2010). The long-term storage of C in soil ecosystems is determined by the balance between the rate of incorporation of new organic matter (OM) in soil and the decomposition of SOM. Variations in soil OC stocks are related to specific soil properties (e.g. pH, texture), to the complexity of physical, chemical and biological processes (e.g., burrowing, microbial activity) that influence C cycling in the soil, and to a number of natural factors (e.g., parent material, topography, vegetation, climate), and human-induced factors, such as land use, management intensity(Mou et al. 2005; Somaratne et al. 2005; Lützow et al. 2006; Gruneberg et al. 2010).

Early studies on SOC (Schnitzer 1986; Stevenson 1994) were aimed at highlighting its key role in playing different ecological functions (e.g., chemical fertility, structural stability, soil quality, agroecosystem productivity); moreover, SOC is essential for evaluating soil and ecosystem functions (Smith et al. 2000; Lopez et al. 2008), for understanding soil carbon sequestration processes (Venteris et al. 2004), and for estimating OC stocks at a national or global scale (Dixonet al. 1994; Batjes 1996). The SOC content, therefore, results an effective environmental indicator, being related to many aspects of agro-forest productivity, ecosystem sustainability and carbon stock. More recently, attention has been focused on the ability of soil to storage and accumulate OC along the soil profile under various land uses (Lal 2005; Mikhailova et al. 2006; Cerli et al. 2009; Schulze et al. 2009), in order to develop strategies of soil management so as to increase the SOC storage and reduce the atmospheric CO_2.

To estimate accurately the organic carbon (OC) stocks in soils is difficult because the relative importance of natural and human-induced factors, and the resulting spatial pattern of OC stocks, are still poorly understood. Until now, there are only few studies where estimates of OC stocks have been calculated based on a high number of direct measurements (Perruchoud et al. 2000; Prichard et al. 2000; Banfield et al. 2002; Kulmatiski et al. 2004; Garlato et al. 2009a,b; Andreetta et al. 2010; Gruneberg et al. 2010). Other studies have examined SOC spatial variability from a relatively small number of representative soil profiles at the plot scale in a range of natural and semi-natural environments (Schöning et al. 2006; Don et al. 2007), and sources of uncertainty affecting soil organic carbon estimates have been recorded by Galbraith et al. (2003) in Northern New York.

In this paper attention is focused on organic C storage in surface layer (0–20 cm) of forest soils under different forest coverage. In particular, we investigated the sequence and nature of surface organic (O, H) and organo-mineral (A) horizons, usually defined as the forest humus (Zanella et al. 2009), i.e., that part of SOM which derives from the degradation and decomposition of animal and plant remains (Zanella et al. 2001). The alteration mechanisms and the chemical structure of humic substances are not completely known, but they have a relevant resistance to chemical-physical degradation, higher than the primary compounds (Piccolo 1996; Wuddivira et al. 2007; Dou et al. 2008). Recent advances in SOM dynamics suggest a link between the humus forms and SOC stabilization (Andreetta et al. 2010); mean residence time and turnover are generally related to the humus forms, and proved much lower in organic than in organo-mineral horizons of forest soils (Schulze et al. 2009), which could represent a significant sink of refractory carbon. However, the relationships between humus forms, SOC stability, and soil carbon stock are not completely known.

Based on this statement, the objectives of this work were: (1) to characterize the humus forms under different forest stands in Alpine environment, (2) to estimate the soil carbon stock for each kind of humus forms, (3) to outline the relationships among humus forms, soil organic matter dynamics,and soil carbon stockwith reference to climate change.

MATERIALS AND METHODS

Study Area

The studied area is located between Cortina D'Ampezzo and Borca di Cadore municipalities, in the Veneto Region (Northern Italy). The geological substrate of the whole area is constituted mostly of calcareous rocks (dolostone and limestone dating back to the Middle Triassic - Lower Cretaceous period), which form soaring cliffs and detritic material disseminated along deep slopes (Bosellini 1996). The climate of the area is influenced by both orography (the highest peaks have an altitude over 3.200 m a.s.l.), and continentality. The continental character is more evident in the Cortina territory (NW of the studied area), where rainfall (maP = 1238) is relevant during summer and minimum in winter, while in Borca di Cadore (SE) rainfall distribution is more homogeneous during all the year (Table 1); hence, it may be inferred that there exists a climatic gradient from NW to SE, which is pointed out also in the phytoclimatic subdivision proposed by Del Favero and Lasen (1993). Based on monthly thermo-pluviometric data from three different meteorological stations within the investigated area (P.so Falzarego, 2100 m a.s.l.; Podestagno, 1314 m a.s.l.; Valle di Cadore, 856 m a.s.l.), the soil water balance was calculated following the Thornthwaite method (quoted in Andreis et al. 2003). Soil moisture regime results *perudic* at higher altitude ($>$1600 m) and *udic* at low altitude.The soil temperature regime is *frigid* for all the soils considered, being maT within the range 0–8°C, with a difference $>$6°C between summer and winter (Table 1).

The forest coverage of the investigated area is influenced by the environmental characteristics (altitude, exposure, microtopography, lithology). According to Pignatti (1981), the Ampezzo Basin (North-West) is included in the Internal Dolomites bioclimatic zone, while the Boite River Valley (South-East) is included in the External Dolomites bioclimatic zone. Del Favero and Lasen (1993), in their framework on the Veneto vegetation, distinguish in the investigated area five different vegetal associations: *Picetum* (Typical Subalpine Spruce), *Pinetum* (Endalpic Scots Pine), *Cembretum* (Typical Swiss Stone Pine), *Laricetum* (Typical Larch), and *Ostryetum* (Hop Hornbeam).

Sampling Sites

For a preliminary selection of the sampling stations, the Geological Map (1:100.000) and the Forest Vegetation Map of Cortina d'Ampezzo (Pignatti 1981) were used. We

Table 1 Selected thermo-pluviometric data from three different meteorological stations within the investigated area: elevation, mean annual precipitation (maP), mean, maximum (MAX) and minimum (MIN) air temperature, and potential evapotranspiration (PET)

Meteorological Station	Elevation (m)	maP (mm)	Air Temperature (°C)			PET (mm)
			MIN	MAX	Mean	
P.so Falzarego	2100	1172	–5.0	10.6	2.1	33.7
Podestagno (Cortina)	1314	1238	–3.6	14.3	5.1	41.1
Valle di Cadore	856	1123	–1.0	17.1	8.0	50.1

selected five sites with similar geological and morphological features, but reflecting differences in elevation, climate, and land cover, and considered by Del Favero and Lasen (1993) as representative forest stands of the studied area: Subalpine Spruce (*Picea abies* (L.) Karsten) at site H1 (elevation 1700 m), Endalpic Scots Pine (*Pinus sylvestris* L.) at site H2 (elevation 1325 m), Swiss Stone Pine (*Pinus cembra* L.) at site H3 (elevation 1800 m), Larch (*Larix decidua* Mill.) at site H4 (elevation 1660 m), and European Hop Hornbeam (*Ostrya carpinifolia* Scop.) at site H5 (elevation 975 m).The identification of soils under the five forest stands was carried out by comparing data collected during the sampling campaign and the information contained in the Soil Map of Cortina D'Ampezzo (Zilioli 2007).

At each selected site, soil pits were excavated for pedogenetic characterization of the soil. Full information about standard pedological analyses is available from the authors. The soils were classified according to the criteria of the last edition of Keys to Soil Taxonomy (USDA 2010) and have been found to belong to three orders. In particular, Entisols (Lithic Udorthents) were found in the Larch stand (site H4), in a portion of land with parent material consisting of mostly calcareous debris. Inceptisols (Humic Lithic Eutrudepts) were found under the Subalpine Spruce stand (site H1), on limestone substrate and with quite pronounced slope. Mollisols (Lithic Haprendolls) were identified under Endalpic Scots Pine stand (site H2), Swiss Stone Pine stand (site H3), and European Hop Hornbeam stand (site H5), with mainly calcareous parent material.

Field and Laboratory Methods

At five points around each soil pit we sampled the surface soil horizons (O and A). A detailed macroscopic description of topsoil was carried out with the help of a field description sheet produced by Green, Trowbridge, and Klinka (1993) and adapted by Calabrese et al. (1996). The morphological description of the organic (OF, OH) and mineral (A, AC) horizons allowed to identify the humus forms according to the French classification (Référentiel Pèdologique - AFES 2009). The following humus forms have been identified: Dysmull at site H1 under Spruce, Tangel, or Lithoamphimus at site H2 under the Scots Pine, Hemimoder at site H3 under the Swiss Pine, Oligomull at site H4 under Larch, and Eu-Amphimus at site H5 under the European Hop Hornbeam.

Topsoil samples were subdivided into horizons immediately after sampling; each horizon was air-dried over one week, then crushed and finally subsamples were sieved at 0.5 mm and 2 mm to separate stones, coarse roots, and soil material. Soil samples <0.5 mm in size were analyzed to determine total organic carbon (TOC), total extractable carbon (TEC), humic carbon (HC), and total Kjeldahl nitrogen (TKN), while soil material <2 mm was analyzed for pH and LOI_{550} (loss on ignition at 550°C; see Table 2). All the analyses were carried out according to the Italian Legislation Acts (DM 13/09/1999–GU N° 248 21/10/1999) except for $LOI_{550,}$ for which the procedure described by De Vos et al. (2005) was followed. Soil pH was determined potent biometrically in a suspension 1:10 soil-water and soil-0.01 M KCl solution. TOC, TEC, and HC were determined by the standard Springer-Klee method (Springer and Klee 1954); the procedure was applied directly to the soil fraction <0.5 mm for TOC determination, while TEC and HC were determined respectively on the liquid phase and on the solid phase (SPE) extracted with a 0.1 M $Na_4P_2O_7 \times 10H_2O + NaOH$ solution. TKN was determined by distillation according to the Kjeldahl method (reported in DM 13/09/1999–GU N° 248 21/10/1999). LOI_{550} was determined according to De Vos et al. (2005), keeping 3 g of dried sample at 550°C for

Table 2 Summary of selected chemical and physical soil properties at the investigated sites: layer thickness (THICK), pH, total Nitrogen (TKN), total organic carbon (TOC), total extract carbon (TEC), humic carbon (HC) concentrations, loss on ignition (LOI), bulk density (BD). Bulk density is calculated by means of five pedotransfer functions available in the literature (JEF = pedotransfer function by Jeffrey 1970; H&B = pedotransfer by Harrison and Bocock 1981; FED = pedotransfer by Federer 1983; HUNT = pedotransfer by Huntington 1989; H&W = pedotransfer by Hollis and Woods 1989); mean BD and standard deviation (SD%) are also reported

SAMPLE CODE	THICK cm	pH	C/N	TKN $g\ kg^{-1}$	TOC $g\ kg^{-1}$	TEC $g\ kg^{-1}$	HC $g\ kg^{-1}$	LOI %	BD JEF $t\ m^{-3}$	BD H & B $t\ m^{-3}$		BD HUNT $t\ m^{-3}$	BD FED $t\ m^{-3}$	BD H&W $t\ m^{-3}$	BD MEAN $t\ m^{-3}$
H1 SPRUCE															
OF	9	5,4	20	13,9	279,1	38,2	31,0	50,2	0,33	0,32	ND	0,22	0,21	0,39	0,29 ± 0,07
A	15	5,9	15	9,6	143,7	12,4	8,6	36,5	0,42	ND	0,53	0,42	0,36	0,49	0,44 ± 0,06
H2 SCOTS															
OF	4	5,0	37	13,9	520,1	95,7	67,6	95,5	0,14	0,12	ND	0,11	0,11	0,21	0,14 ± 0,04
OH	7	5,0	38	12,4	471,0	86,7	71,1	93,4	0,15	0,12	ND	0,12	0,12	0,24	0,15 ± 0,05
A	10	7,8	11	7,2	77,3	4,6	3,9	25,4	0,53	ND	0,65	0,66	0,55	0,54	0,59 ± 0,06
H3 SWISS															
OF	5	6,2	26	14,7	385,1	75,1	58,5	74,4	0,21	0,20	ND	0,15	0,15	0,31	0,20 ± 0,06
A	12	7,4	15	16,3	246,9	35,1	29,6	60,1	0,27	ND	0,36	0,25	0,23	0,41	0,30 ± 0,07
H4 LARCH															
A	18	7,4	14	6,1	87,4	4,9	4,2	29,4	0,49	ND	0,60	0,61	0,51	0,53	0,55 ± 0,05
H5 HORNBEAM															
OH	3	7,8	13	24,1	318,7	61,2	46,5	68,0	0,24	0,22	ND	0,19	0,18	0,36	0,24 ± 0,06
A	12	8,0	9	12,9	121,9	8,9	6,1	28,8	0,49	ND	0,61	0,48	0,41	0,50	0,50 ± 0,07

three hours. The OM content is estimated through weight loss; since at that temperature there is not carbonate breakdown, inorganic carbon contribution is not included in OM calculation.

Soil Bulk Density and Soil Organic Carbon Stock Estimates

Soil organic C stock (SOCs) for each horizon was calculated applying the following equation (Schwager and Mikhailova 2002):

$$\mathrm{SOCs} = \sum_{\mathrm{n}=1}^{\mathrm{K}} (\mathrm{C} \times \rho \times \mathrm{T} \times (1 - \delta) \times 10) \tag{1}$$

where SOCs is the stock of organic carbon per unit area (t ha^{-1}), C is the concentration of organic C in the $\leq$ 0,5 mm soil fraction (g kg^{-1}), ρ is the soil bulk density (t m^{-3}), T is the layer thickness (m) and δ is the proportion of coarse material (>2 mm in size).To apply the above equation, the bulk density (BD) value is required, a parameter that is difficult to calculate directly from humus forest soils samples (Hedde et al. 2007; Schulp et al. 2008), and is frequently estimated by means of pedotransfer functions (Garlato et al. 2009b; Goidts et al. 2009). Yet, some studies (ARPAV 2006; Garlato et al. 2009a) have focused on uncertainties in SOC stock assessment and have demonstrated the importance of directly measuring the soil BD, while indirect estimates based on pedotransfer functions can lead to errors from 9% up to 36% of the SOCs (Goidts et al. 2009). On the other hand, Schulp et al. (2008) have demonstrated that there are several difficulties in measuring BD in forest soils, due to the extreme variability of the humus thickness, the presence of stones and roots, the risk of compaction during sampling. For this study, five pedotransfer functions available in the literature (see De Vos et al. 2005, and references therein) were selected according to their predictive capability, and to the availability of the predictor variables requested, as reported by De Vos et al. (2005).

RESULTS

Soil Chemical-Physical Characteristics

The five topsoils included both organic (OF, OH) and organo-mineral (A) horizons. Data concerning topsoil chemical-physical characteristics are reported in Table 2. Topsoil thickness varies from 24 cm at site 1 to 15 cm at site 5, depending on topography, parent material, and land cover. The pH ranges from subacidic (5.0 at site 2 under Scots Pine) to subalkaline (8.0 at site 5 under Hornbeam).

Total Nitrogen (TKN) ranges between 6,1 g kg^{-1} in the A horizon at site H4, to 24,1 g kg^{-1} in the OH horizon at site H5, while total organic Carbon (TOC) ranges between 77.3 gkg^{-1} to 520.1 gkg^{-1}, the lowest values being those of the A horizons, whereas the highest are those of the OF horizons. The resulting C/N ratios are higher in the OF-OH horizons than in the A horizons, suggesting a higher mineralization rate to occur in the latter. The broadleaf forest floor at site 5 proved the most mineralized, and the Scots Pine stand at site 2 the least one. The total extractable carbon (TEC) is higher in organic horizons in comparison to the A horizons; at site 2, TEC presents the highest amount (182.4 gkg^{-1}), while the least was recorded at site 1 under spruce (38.2 gkg^{-1}). Humic carbon (HC) amounts present similar distribution than TEC, with the least values in the A horizons, as well as loss on ignition (LOI).

We calculated the bulk density (BD) of topsoils by means of PTFs available in the literature (De Vos et al. 2005). The related values are reported in Table 2 together with mean value and standard deviation (SD). There is good agreement among the different PTFs values, with slight differences, for both the organic and organo-mineral horizons, the least BD value being that of the OF horizon at site 2 (0.14 tm^{-3}), and the highest that of the A horizon at site 2 (0.59 tm^{-3}), as expected.

Soil Carbon Stock Calculation

The investigated sites present typical features of alpine soils developed from calcareous materials: little horizonation, humus accumulation, limited soil depth, large amount of skeleton, subalkaline reaction, loamy texture (Zilioli and Bini 2009). One important feature is the relative proportion of coarse fragments ($>$2mm in size) per unit volume, that may influence the carbon stock in the whole profile (Corti et al. 2002). Another important feature to consider in evaluating OC stock is the variability of soil thickness, which in turn is a function of topography, vegetation cover and soil development. In order to take into account these two fundamental aspects in calculating the SOC stock of the investigated sites by the equation (1), we have considered four different scenarios, two related to the actual soil thickness (including and excluding coarse fragments), and two related to a potential scenario where a soil thickness of 10 cm is considered (including and excluding coarse fragments, as in the previous two scenarios).

The SOC stock calculation in the real scenario, both including and excluding the coarse fraction, is reported in Figure 1 (top). It allows evaluating the current soil capacity to block carbon in the organic form in the investigated profiles. Poorly evolved humus forms as Hemimoder (H3), and thick humus as Dysmull (H1), store more carbon, although this depends marginally on the type of humus, since in this scenario horizons thickness and the amount of coarse material (roots and stones), play a key role. In fact, comparing the average values of carbon stored by different humus forms and the horizon thickness (Figure 1), at site H2 a moderately evolved humus form (Lithoamphimus) stores 100tha^{-1} on average, and the Dysmull at site H1 stores 151 tha^{-1} on average.

SOCs values found at the investigated sites are consistent with those reported by Garlato et al. (2009b). In fact, in the present study a SOCs average of 7 t ha^{-1} cm^{-1} was found, which is consistent with 9 t ha^{-1} cm^{-1} found by the previous authors for organic horizons in the Veneto region. However, they estimated the bulk density (BD) by the Hollis and Wood (1989) pedotransfer function, which is known to be influenced by an overestimation error (Garlato et al. 2009a).

The presence of the coarse fraction in the profile reduces the OC storage capacity, since the available volume of fine earth ($<$2mm) is reduced; therefore, in order to investigate how much the coarse fraction influences the SOCs estimate, we calculated the SOCs on the real horizons thickness but excluding the coarse fraction (Figure 1, bottom).

The comparison between carbon stocks considering the coarse material, or excluding it, shows its importance in the assessment of the humus capability to sequester carbon (Figure 1); in fact, the coarse material decreases the average C stock about 20% at site H2, around 30% at site H5, and over 40% at site H4, with respect to the sole fine material. Yet, the general trend concerning all the examined samples is shown in the 2nd scenario (Figure 1, bottom); although in terms of C tons per hectare there are differences between

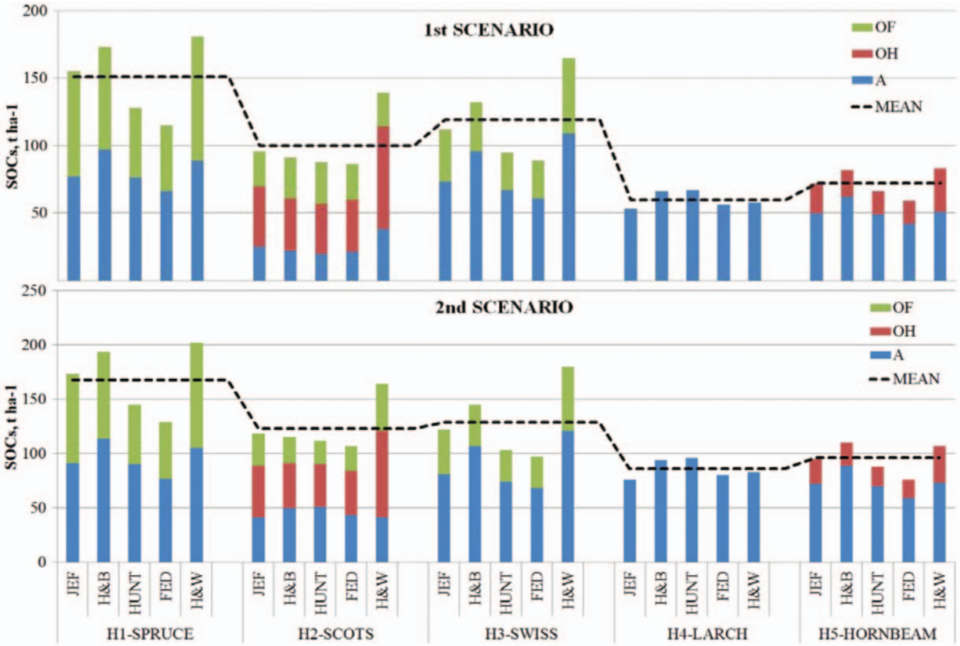

Figure 1 Calculation of the real SOC storage for the different forest stands including coarse material (top) and excluding it (bottom), with reference to five pedotransfer functions. The SOC contribution of various soil horizons at each site is shown (color figure available online).

the stocks calculated including, or excluding, the coarse fraction, the humus thickness is the main driving factor. However, it cannot be excluded that different humus forms might influence SOC storage as well.

In order to overcome the recorded differences in humus thickness, and to estimate the inherent potential of different humus forms to sequester carbon, we calculated the average OC (tons per hectare per cm) stored at every site in a potential scenario (Figure 2), i.e. considering a soil thickness of 10 cm for each profile.

The potential scenario shows a different trend with respect to the real one. Yet, the potential carbon stock is greater under the Swiss Pine stand (H3, average 71 t ha^{-1}), than under the Spruce stand at site H1 (average 66 t ha^{-1}), in comparison to the real scenario. Moreover, the differences between Amphimus forms at sites H2 (Swiss Pine) and H5 (Hornbeam) are strongly reduced in the potential scenario (Figure 2), indicating a similar storage capacity, although vegetation cover, climate, and altitude are quite different. Oligomull form under Larch (H4) shows less capacity to store carbon due to a faster process of OM decomposition (Zanella et al. 2001; Jabiol et al. 2007), which does not allow formation of thick organic horizons.

The potential scenario proposed in Figure 2 (bottom), where both total horizon thickness and coarse fraction are not considered, presents the same trend shown in the previous one (Figure 2, top). The recorded trend is consistent with what is supposed in the French humus classification (Zanella et al. 2001; Jabiol et al. 2007; Zanella et al. 2009), i.e., the poorly evolved and less active humus forms as Hemimoder and Dysmull, typical of high altitude and acidifying vegetation coverage (Swiss Pine and Spruce), have high storage capacity, since conifer litter holds components that are more difficult to decompose, resulting in litter accumulation at the forest floor and formation of acid compounds (Schulpet

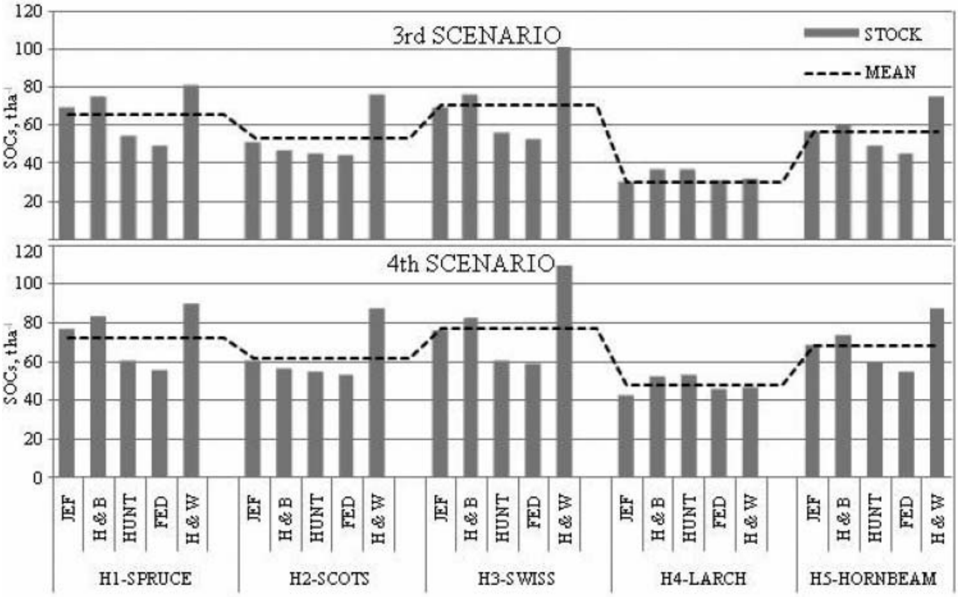

Figure 2 Estimate of the potential SOC storage in 10 cm soil for the different forest stands including coarse material (top) and excluding it (bottom), with reference to five pedotransfer functions.

al. 2008). According to the potential scenario, including the coarse material, in this study 71 t ha^{-1} C have been found for Swiss Pine Hemimoder, while the humus forms with moderate evolution, such as Amphimus (Scots Pine and Hornbeam coverage, at sites 2 and 5, respectively), store around 55tha^{-1}, and the most evolved humus form as Oligomull (Larch stand at site 4), stores only 30tha^{-1}. Therefore, with respect to the Hemimoder, a SOCs reduction of 22% and 57%, respectively, was recorded in the last two humus forms, as a consequence of both lacking organic horizons and a faster mineralization process.

A positive correlation ($P<0.05$) between SOCs and altitude was observed (Figure 3), since at higher elevation there is a rise in the average thickness of the organic horizons, as well as an increase in carbon content, which is reflected in carbon stock increase. Both the graphs reported in Figure 3 present a tendency to increasing SOCs values with altitude, the real scenario (full line) showing higher values and more pronounced differences among the various sites, while the potential scenario (dotted line) shows more uniform values. The larch stand seems to be the most critical one in both the scenarios.

DISCUSSION

The average SOC storage of the five samples in the potential scenario is 55 ± 16 t ha^{-1} 10 cm^{-1}, which is consistent with data reported in literature on calcareous soils of the Trentino Alps (Garlato et al. 2009a), where the SOCs average is 53.2 t ha^{-1}10 cm^{-1}. This result is quite far from the results found by Schulp et al. (2008) for O horizons of the Netherlands soils with conifers coverage (Scots Pine and Larch) and by Olsson et al. (2009) for O horizons of Swedish Podzols with forest coverage; in fact they found 27.57 t ha^{-1} and 28 t ha^{-1}, respectively, on a soil thickness of about 8 cm. On the other hand, Olsson et al. (2009) highlight also that in Norway forests in the same conditions the average SOCs is about 50 t ha^{-1}, very close to the average value reported in this paper.

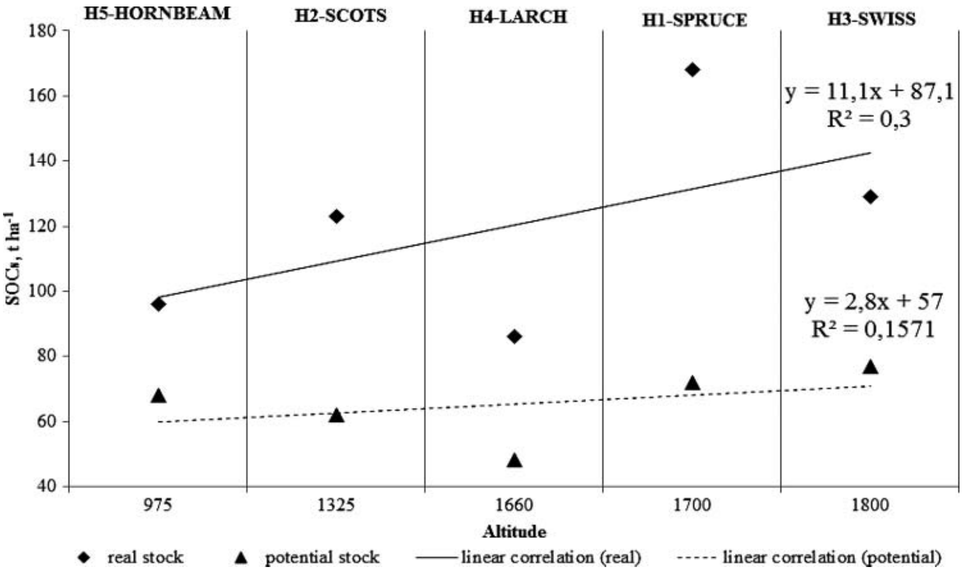

Figure 3 Regression analysis showing relationships between altitude (m a.s.l.) of the sites investigated and calculated real (full line) and potential (dotted line) carbon stocks (t ha$^{-1)}$.

Data related to the 4th scenario (Figure 2, bottom) show that the presence of litter, especially if it is thick and slightly degraded, as that deriving from resinous plant remains, is a key factor for carbon sequestration; indeed, average SOC stored in forest soils is far in excess with respect to cultivated soils, steppes or grasslands, where the litter input is minimal (Cerli et al. 2009). In particular, conversion of forest to agricultural ecosystems invariably results in the depletion of SOC stock by 20–50% (Lal 2005), as it is demonstrated by several studies (Oorts et al. 2007; Schulp et al. 2008; Olsson et al. 2009; Wang et al. 2009; Kaiser et al. 2011; Powlson et al. 2011).

In the cited papers, SOCs estimate is lower than those calculated for forest soils, irrespective of the soil thickness, suggesting litter originated by forest cover to be more effective in C storage (Lagagnière et al. 2010).

Forest soils too show some variability in SOC storage. In fact, the SOCs average values recorded in this study differ from those reported by Solaro and Brenna (2005) for the soils of Central Alps (87 t ha^{-1}30 cm^{-1}), as well as those reported by Petrella and Piazzi (2005) for Western Alps (91 t ha^{-1}30 cm^{-1}). Therefore, a decrease of SOCs is evident following a W-E transect along the Alps, and this is consistent with studies carried out by Fantappiè, L'Abate, and Costantini (2010).

Climate has a fundamental effect on soil properties and processes, and may influence carbon sequestration/release in forest soils. For instance, Melillo et al. (2002) observed that soil warming accelerated the mineralization process of OC and CO_2 fluxes to the atmosphere. Yet, an increase in global temperature may result in a long-term loss of the SOC stock, converting forests to carbon sources and triggering a positive feedback between CO_2 emissions and global warming (Lal 2005; Pilli 2006; Tedeschi 2007).

Organic horizons with relatively short turnover rate are particularly vulnerable to climate change or other disturbances, as change in soil use and management (Schulze et al. 2009).The driving forces that control the humus decomposition rate are litter type and climate. Climate is the dominant factor in areas subject to extreme weather conditions, as in mountain regions. In particular, OM mineralization rate is directly related to potential evapotranspiration (PET) and temperature (Coûteaux et al. 1995; Lal 2005). Yet, the sites at higher altitude (H1-Spruce, H3-Swiss), where PET and mean annual temperature (maT) have the smallest values, present less active forms of humus, which accumulate thick organic layers and great amounts of SOC, while at site H4 (Larch stand), where PET and maT increase, mineralization rate also increases, as reported by Calabrese et al. (1996) and Zanella et al. (2001).

Climate as single driving force, however, cannot explain the peculiarity of Amphimus forms, which is typical of a transitional ecosystem that has not yet attained the steady state (Chersich et al. 2007).

At lower altitude (sites H2 and H5), with mitigation of climate conditions, an increased importance of litter and substrate as driving forces is recorded. Indeed, at site H2 the forest floor is composed of organic residues associated with high contents of lignin, resins, and waxes, and low nitrogen content (Zanella et al. 2001; Lal 2005),that make them unattractive to soil microorganisms. The forest floor at site H5 should have enhanced mineralization processes, and improved soil fertility; unlikely, the humus form (Amphimus) is poorly active; it is likely that the calcareous parent material blocks the “secondary mineralization” of the litter (Zanella et al. 2001), slowing the OM decomposition.

CONCLUSIONS

Carbon sequestration in the top layer of forest soils in Alpine environment would result from the influence of interacting factors such as humus type and climate. A clear correlation is established between the humus forms and SOCs. The most evolved humus (Oligomull) presents the lowest values of SOCs, and the little evolved forms (Hemimoder and Dysmull), the highest values.

The main driving factor for SOC storage is climate, which controls the thickness of the organic horizons and the OM decomposition rate. Evidence is given by the positive correlation between SOCs and altitude. However, current knowledge about the SOM dynamics (humification rate, mineralization, stabilization) is still limited.

The variability of the recorded SOCs values demonstrates the criticism represented by the BD estimate by PTFs, since it is affected by under- or over-estimation. Yet, the assessment of SOCs data highlights net relationships between humus forms and potential SOCs, but it is not possible to quantify with certainty the actual difference in storage capability of each humus form. Future studies on SOC storage should use pedotransfer functions calibrated on a local dataset of BD in order to minimize this concern.

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