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Forest conversion to poplar plantation in a Lombardy floodplain (Italy): effects on soil organic carbon stock

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Abstract

Effects of forest conversion to poplar plantation on soil organic carbon (SOC) stocks were investigated by sampling paired plots in an alluvial area of the Ticino river in Northern Italy. According to land registers and historical aerial photographs, the two sites were part of a larger area of a 200 years-old natural forest that was partly converted to poplar plantation in 1973. The soil sampling of three layers down to a depth of 100 cm was performed at 90 and 70 points in the natural forest (NF) and in the nearby poplar plantation (PP), respectively. The substitution of the natural forest with the poplar plantation strongly modified soil C stock down to a depth of 55 cm, although the management practices at PP were not intensive.

By evaluation of equivalent soil masses, the comparison of C stocks (organic layer included) between the different land uses showed a decrease in SOC of 5.7 kg m^{-2} after 37 years of poplar cultivation, corresponding to more than 1/3 of the initial organic carbon content. The land use change from NF to PP not only affected the stock but also the vertical distribution of SOC: ploughing led to the transfer of SOC from soil surface into the deeper layers resulting in a more uniform allocation of organic carbon in the ploughed layer and disappearance of the SOC stratification observed in the forest.

1 Introduction

Soils play an important role in the global carbon cycle representing the major midterm reservoir of organic carbon from photosynthesis. The global reservoir of SOC is estimated to be 1500–2000 Gt C compared to 500–700 Gt C in the biomass (IPCC, 2000; Lal, 2004). Considering an atmospheric reservoir of 760 Gt C as CO_2, a 5 % shift in SOC stocks in global soils might change atmospheric CO_2 by up to 16 % (Baldock, 2007). Globally, the annual carbon uptake in gross primary production of the terrestrial biosphere is estimated at 120 Gt C. At the time scale of decades, almost all assimilated CO_2 flows back into the atmosphere due to major losses by plant respiration, decompo-

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sition and natural disturbances, and only about 1 Gt C is stored annually as net biome production mainly in the soil (IPCC, 2000), indicating that accumulation of current SOC is a very slow process extending over centuries, whereas losses of SOC can be very fast.

Land use by man has always reduced the amount of carbon accumulated by natural terrestrial ecosystems, but the losses since 1850 are estimated to be larger than during all periods of human activity before (Houghton, 2012). Global losses of terrestrial organic carbon in the period 1850–2000 were estimated at 156 Gt, mainly from tropical deforestation, with a contribution of 3/4 from biomass and 1/4 from soil (Houghton, 2003). Soil carbon losses can be attributed mainly to agricultural activities such as drainage, tillage and elevated extraction of biomass; the basic process behind this is the combination of enhanced decomposition of the SOC reservoirs and reduced input of organic matter. A reduction in SOC is linked to a general degradation of chemical, physical and biological soil properties, with the overall effect of reduced fertility, biodiversity and resilience of the ecosystem (Nieder and Benbi, 2008).

Consequently, the protection of soil organic matter (SOM) is considered in various policies and strategies; in the European Union, the "Soil Thematic Strategy" (COM (2006) 232) has established common principles to maintain and increase levels of organic matter and to protect the main soil functions from a series of environmental stressors. In the context of inventories of emissions and sinks of greenhouse gases under UNFCCC and its Kyoto Protocol, the stock changes of SOC need to be reported annually by all Parties under the category Land Use, Land Use Change and Forestry (LULUCF); however, neither soil carbon stocks, nor their changes can be measured easily, and there are very few data available (Jones et al., 2005; Poeplau et al., 2011).

This is especially true for the Po-valley in Northern Italy where thick oak forests and swamps covering once all the area were almost totally transformed into intensive croplands of maize, wheat, rice and woody croplands, mainly poplar plantations under various rotation regimes between two and fifteen years. In Italy, poplar plantations on agricultural lands are explicitly not considered as forest in order to provide some flexibility to farmers to return these lands back into non-woody croplands.

We present here the results of a paired plot study in Northern Italy, comparing a remnant of natural forest representing the original vegetation of the Po Valley with a poplar plantation which was established in 1973 on lands covered before by the same type of natural forest. We selected the two sites because (i) they were comparable with regard to pedological conditions, (ii) the history of the area and the land use change was well documented, (iii) the period since the transformation was long enough to allow the poplar plantation to achieve its typical agroecosystem properties (IPCC, 2003, 2006; Poeplau et al., 2011). To our knowledge, the transition from natural forest to a woody cropland has not been studied before. The goal of our study was to quantify the impact of such land use change on SOC stocks.

2 Materials and methods

2.1 Study site

The site is located within the "Parco Regionale del Ticino", Italy, about 10 km north-west of the city of Pavia (45°12′22″ N; 9°3′35″ E). It is represented by a poplar plantation (PP) and a relic of a natural floodplain forest (NF), the "Riserva Integrale Bosco Siro Negri", about 1 km away from each other (Fig. 1). NF represents the natural land cover of the area, the Padanian-Illyrian hardwood alluvial forests in transition to the mesophytic Padanian mixed oak forest, together covering an area of more than 40 000 km^2 or 80 % of the overall Po plain (Bohn et al., 2003). The landscape was mostly forested (dominated by deciduous oaks – *Quercus* spp. – and hornbeam – *Carpinus betulus*) between the 16th century BC and the 10th century AD, i.e. until the late Middle Age clearings (Ravazzi et al., 2013). The woods were substituted by intense agriculture, with rice and corn cultivation (since the 16th century AD), and poplar cultivation (since the early 19th century). The remnant NF wood, with a size of about 11 ha, received

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the highest level of protection as a “Riseva Integrale”, as it represents one of the few and best conserved relics of the original alluvial forest along the Ticino river. It was not managed for at least 70 years. Historically it has always been forested as a hunting reserve of noble families from nearby Pavia with only occasional removal of precious trees; pasture and removal of fuel wood or litter by local people was strictly forbidden.

Land registers reveal that in the early 1900s the whole area indicated in Fig. 1 was covered by forests of the Bosco Siro Negri type. According to aerial photographs the study area, which is now a poplar plantation, was forested till 1954; the conversion to a poplar plantation took place in 1973, one year before constitution of the Parco Ticino, and appears to have been concluded in 1975. In 1954 the area between NF and PP was already converted from forest to croplands and poplar plantations; on the basis of aerial photographs in 2007 this area appears recently reforested.

NF includes some 15 species in the tree layer, with common oak (*Quercus robur*) dominant and field elm (*Ulmus minor*), field maple (*Acer campestre*), scots pine (*Pinus sylvestris*), black locust (*Robinia pseudacacia*) co-dominant (Motta et al., 2009); the latter specie was absent or rare in 1969 (Tomaselli and Gentile, 1971) but now occupies the borderline with the non-forested area. Common hazel (*Corylus avellana*) and common hawthorn (*Crataegus monogyna*) are dominant in the shrub layer. The humus form, according to Référentiel Pédologique (Baize and Girard, 2008), is mainly Mesomull (Ferré et al., 2005) with subordinate presence of Eumull and Dysmull.

Most of the PP area is now under 3–4 generations of poplar (Clone I-214 *Populus x euroamericana*) with rotation period of 13–14 years. After each harvesting of poplar, the residues are removed and stumps are drilled to allow mouldboard ploughing 50–55 cm deep before establishing a new plantation (6 m × 6 m distance, 278 trees per ha) by insertion of 4–5 m long shoots to a depth of 1.5 m in the soil. The intensity of poplar management is low and includes fertilization (300 kg ha^{-1} urea every 2–3 years) and removal of ground vegetation by harrowing (about 15 cm in depth) and not by chemical weeding; irrigation is never applied.

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Due to proximity to the river Ticino, both sites are subject to periodic flooding (3 times in 10 years, Motta et al., 2009) and the dynamics of the Ticino make their surface morphology and spatial distribution of soil characteristics highly variable. At the study sites, soils do not exhibit a high pedogenetic degree since they developed on recent alluvial deposits of the Ticino river; according to the WRB classification (IUSS Working Group WRB, 2007), they are Haplic Arenosols and Haplic Regosols, with Humic, Eutric and Arenic as common suffix qualifiers (Table S1). The climate of the site is temperate continental, as monitored by the long-term meteorological station at Pavia (1950–2000), with yearly average rainfall of 912 mm and mean air temperature of 12.5 °C.

2.2 Soil, litter and leaf sampling

The effects of forest conversion to poplar plantation on SOC stock were investigated by sampling paired plots whose comparability was confirmed through a reconstruction of land use history of the study area. Nine soil profiles (4 at PP site and 5 at NF site) were opened down to C horizon, described and sampled. Soil samples were taken from each horizon and analyzed. Due to the alluvial origin of the soils and based on soil profiles, for the SOC stock characterization we sampled accounting for soil variability. The sampling was performed during summer 2010, using a gouge auger, applying a random scheme. The maximum sampling depth was set to 100 cm, since LUC was assumed to have no impact on greater soil depths; the layer thickness was set based on vertical distribution of SOC and the average limits between horizons, according to soil profiles.

At PP, soil sampling was carried out in a rectangular area of about 3 ha. Soil samples were collected at 70 points from 3 layers: 0–15 cm (average harrowing thickness, corresponding to the Ap1 horizon), 15–55 cm (corresponding to the lower part of the Ap horizon, ploughed at the beginning of a rotation period) and 55–100 cm (corresponding to the C horizon, never affected by ploughing). The organic layer was absent. Due to the heterogeneity of forest vegetation, at NF the soil sampling was more detailed compared to PP: 90 points were sampled in an area of about 1.3 ha, at 3 depths: 0–10 cm

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(corresponding to the average thickness of the A1 horizon, as observed in soil profiles, i.e. the layer with the greater SOC content), 10–55 cm (the lower limit taken in parallel to PP) and 55–100 cm. For each sampling point, samples of the organic layers were taken in autumn, collecting 35 cm × 35 cm litter biomass, oven-dried at 70 °C for 48 h and weighed.

For each site, soil bulk density (BD) was determined (first two layers) by the cylindrical core method, on undisturbed core samples of 100 cm^3 volume considering the volume of stones, when present; for the lowest layers a pedo-transfer functions was applied using the negative relationship between BD and SOC and sand content set on the first two layers (pedo-transfer function (1) for PP: $1.56 - 0.0015 \times d - 0.0307 \times C$; pedo-transfer function (2) for NF: $1.096 - 0.0042 \times d - 0.0058 \times C + 0.002 \times s$; where d is the depth (cm), the C is organic carbon in g kg^{-1} and s is the sand content in g kg^{-1}). Newly fallen leaves of poplar and of the Bosco Negri main wood trees (five samples for each tree type) were collected from the forest floor in autumn, immediately after their falling.

2.3 Soil chemical and physical analysis

On samples taken from the soil profile, organic C and total N (Flash EA 1112 NC-Soil, Thermofisher Scientific CN elemental analyzer, Pittsburgh, USA), pH_w (soil-to-solution ratio of 1 : 2.5), soil texture (sieving and sedimentation; 5 fractions) and cation exchange capacity (NRCS, 2004) were determined. Organic C, total N and pH_w were determined on all samples collected through soil coring. The determination of soil texture was carried out for the first two layers on all the samples while for the third layer it was done in correspondence to 20 sampling points selected as representative of the heterogeneity of the other soil parameters. For BD determination, soil samples were oven dried at 105 °C for 48 h and weighed; for soils containing coarse material (> 2 mm), soil volume was reduced considering the volume of stones. The OC and total N concentration of litter layers was converted to the content per area unit (kg m^{-2}). The soil C and N content on the area basis was computed for all sampled mineral layers on

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the basis of soil BD. C and N contents were also determined on litter and newly fallen leaf samples. The presence of carbonate was investigated and they resulted absent in soils of both the sites.

2.4 Mass correction

Major errors are linked to quantification of change in SOC stocks and other soil properties to fixed depths compared with the quantification in equivalent soil masses (Jenkinson, 1971; Ellert and Bettany, 1995). In this study the comparison of C stocks of the 0–55 cm layer between the different land uses was made by evaluating equivalent masses (Poeplau et al., 2011), accounting for differences in soil BD. The conversion from forest to agricultural soils usually leads to a change in soil BD due to tillage which breaks aggregates and compacts soil (Murty et al., 2002). Calculation of SOC stocks as a product of concentration, bulk density and soil depth is insufficient for assessing SOC stock changes, as it fails to account for tillage effects and consequently for the influence of different soil masses (Ellert and Bettany, 1995; Wendt and Hauser, 2013). The highest soil mass in a single point (reference soil) from 0 to 55 cm depth (836 kg) was measured at PP. All the other soil masses of both the sites were aligned: the correction was carried out making use of the deepest layer adding thickness to match the mass of the reference soil.

2.5 Statistical and geostatistical analyses

Statistical and geostatistical analyses were done by using the software package ISATIS, 13.01 (Geovariances, 2013). Exploratory data analyses were performed for organic carbon, sand, silt and clay content, pH_w and C : N ratio of samples taken through coring. The spatial structure of SOC stock was examined with experimental variograms. A spatial pattern of SOC stock was revealed for the PP site only, using the intrinsic random functions of order *k* (IRF-*k*) technique of non-stationary geostatistics (Matheron, 1973; Buttafuoco and Castrignanò, 2005): it decomposes the drift and covariance

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structure to define models of spatial covariance through increments of a sufficiently high order, so that the drift can be filtered out and stationarity attained. The goodness of the selected model was evaluated with a cross-validation test by calculating: (1) the mean error, which proves the unbiasedness of the estimate if its value is close to 0, and (2) the variance of the standardized error; if the model is accurate, the variance of the standardized error should be close to 1.

The lack of spatial structure at the investigated scale led to consider the NF sampling points as independent from each other; their average (± standard error) represents the mean SOC content of the forest soil. At PP, the spatial relationship between the pseudo-replicates (Hurlbert, 1984) was identified and modelled. The SOC stock was interpolated using IRF-*k* kriging (Matheron, 1973) in which an auxiliary variable (coarse sand content) was incorporated as external drift function;. a cumulative C stock value for the whole area was computed as the sum of values relative to each square meter of the estimation map and converted to the stock per area unit ($kg\,m^{-2}$). For the PP site, a geostatistical analysis of the soil content of coarse sand (2–0.1 mm) was performed too, with the aim of understanding its spatial distribution (using ordinary kriging) and identify homogeneous zones for each of which a cumulative SOC value was calculated.

3 Results

3.1 Soil profile description

The soil profile descriptions presented in Tables S1 and S2 show a general homogeneity of soil properties along the profile for the PP site, whereas soils in the NF site exhibited a high differentiation of soil properties along the profile The A1 horizon in NF was characterized by higher SOC ($54.2\,g\,kg^{-1}$), lower pH_w values (5.6) and BD ($0.96\,g\,cm^{-3}$) and finer soil texture (sand: 38.2 %; silt: 48.7 %; clay: 13.2 %) than the deeper horizons; soil properties sharply changed with depth. The SOC strongly decreased in the A2 horizons and was very low in the C horizons. The fine material and the cation exchange capacity highly decreased with soil depth while BD and pH increased.

A humus layer was found in the NF site only; it was predominantly composed of common oak leaves and, to a lesser extent of black locust, field maple, common hazel, black poplar, common aspen and common hawthorn leaves. The average C content was 380.3 g kg^{-1} at a C : N ratio of 19.2 (Table 1).

3.2 SOC, physical and chemical soil properties

Results of the coring survey (Table 1) showed average SOC of 51.5 g kg^{-1} in the topsoil (0–10 cm) of the NF site, which decreased with increasing soil depth. Compared to the surface content, less than half the C and N content was present in the second investigated layer (10–55 cm) and very low values of 3.3 g kg^{-1} characterized the soils below 55 cm. At PP site we observed that SOC was distributed evenly to a depth of 55 cm, which corresponded to the maximum limit of ploughing; its content was 11.1 g kg^{-1} and 9.7 g kg^{-1} in the layer 0–15 cm and 15–55 cm respectively. Below 55 cm the SOC decreased to 3.8 g kg^{-1}. For both sites, the texture (USDA class) of the topsoil was mainly sandy loam. In the 10–55 cm layer the soil texture of NF site was mainly sandy loam or loamy sand (sand: 69.6 %, silt: 26.0 %, clay: 4.4 %) while the last investigated layer (55–100 cm) showed predominantly a sandy soil texture (sand: 84.2 %, silt: 13.7 %, clay: 2.1 %). At PP, soil texture remained sandy loam till the deepest layer (sand: 48.4 %, silt: 45.8 %, clay: 5.8 %).

The undisturbed soils of the forest showed a BD of 0.99 g cm^{-3} in the 0–10 cm layer, which increased to 1.28 in the 10–55 cm layer and 1.51 in the 55–100 cm layer. At the PP site, the topsoil showed a BD of 1.21 g cm^{-3}; the other sampled layers had similar soil BD, with slightly higher values in the lowest layer. Under forest, soil average pH_w values were less than 5.0 in the first and second layer (4.6 ± 0.05 and 4.7 respectively); soil pH_w value increased in the 55–100 cm layer to an average value of 5.3. At PP, average pH_w value was 5.9 in the topsoil, with a minimum of 5.5 and a maximum of 6.4. It slightly decreased with depth, reaching a value of 5.7 both in the second and third

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investigated layers. The intra-site spatial variability was high for SOC and texture; the coefficients of variation (CV) for these parameters were above 35 % (data not shown).

The chemical characteristics (OC and total N content and C : N ratio) of leaves of *Populus x euroamericana* and some dominant and co-dominant NF species (*Quercus robur*, *Acer campestre*, *Corylus avellana* and *Robinia pseudacacia*), which constituted the main epigeic organic matter inputs to soils, are reported in Table 2. The leaves of common oak were characterized by lower total N content and higher OC content than those of the other vegetation types and showed a C : N ratio of 50.3. The C : N value decreased to 42.2 in leaves of field maple and to 32.3 ± 1.5 and 30.1 in leaves of poplar and common hazel respectively; false acacia leaves were characterized by very high N content (3) and a very low C : N ratio (14.08).

3.3 Spatial variability of SOC stock

The spatial variability of the SOC stock in the 0–55 cm layer was explored for both sites. The two investigated land uses differed from each other. For NF there was no spatial autocorrelation in the SOC data (pure nugget effect), while the experimental variogram of PP appeared not to be upper bounded, indicating the non-stationarity of SOC (data not shown).

In fact, the spatial variation of SOC stock of PP soils exhibited a trend along with the sand content: the Generalized Covariance (GC) model was a nested model, which comprised a nugget effect and a linear structure (order $k = 1$). The spatial estimates of SOC stock showed a distribution inverse to that of the coarse sand content: SOC was lower in soils with higher coarse sand content while higher SOC stocks characterized finer textured areas (Fig. 2).

3.4 SOC stock comparison between land uses

A SOC stock of 14.2 (ranging between 6.2 and 23.9) kg m^{-2} characterized the investigated thickness down the profile to 55 cm (litter layer included and accounting for

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0.5 kg m^{-2}) at the NF site (Fig. 3). At PP, the SOC content was 8.5 (ranging between 4.3 and 10.7) kg m^{-2} in the 0–55 cm layer, 40 % less than that observed for the forest land use. The SOC changes owing to land use conversion resulted more pronounced in soils with coarser texture: losses of 48 and 61 % were observed for coarse (2–0.1 mm) sand contents ranging between 14–56 and 56–83 % respectively (Fig. 3).

4 Discussion

4.1 SOC sampling and comparison methodology

To achieve comparability of SOC stocks between the two neighbouring sites, we performed soil sampling by depth increments and compared equivalent soil masses. The conversion of forest to poplar plantation affected the first two layers only, as showed by descriptions and analyses of soil profiles and corings; the ploughed limit never exceeded the depth of 55 cm and the average SOC content of the third layer of the PP site was low and comparable with that found at the same depth in the forest soils. For these reasons, we can assume that the last investigated layer might be the soil parent material and that originally the soils were similar in SOC content.

The detailed sampling carried out in the study sites allowed to characterize the variability of soil characteristics and to understand the changes both in stock and vertical distribution of SOC after land use conversion, differently from what was obtained in the same study area by Cerli et al. (2009), who sampled only four soil profiles to a depth of 60 cm for each site; the sampling approach they applied made it possible to observe only a SOC redistribution along the soil profiles but not a change in SOC amounts as a consequence of the transformation of the natural forest to the poplar plantation.

We compared the two sites and obtained the SOC stock variation owing to 37 years of poplar cultivation; despite it was not a statistical inference (Webster, 2007), the magnitude of the differences between the means of the sites was considerable and further

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increased if the comparison was done for soils with coarse sand content higher than 55 %; moreover, the range of variation relative to each average value was narrow.

Through the geostatistical analysis we modelled the spatial structure of the SOC stock in the 0–55 cm layer. The analysis showed differences between the two environments, in terms of spatial structure and SOC contents, reflecting the divergence that occurred in the PP soil after deforestation: while for the natural forest the SOC stock was not autocorrelated, a linear trend of SOC along with the coarse sand content was instead observed at PP. The geostatistical approach, taking into account the spatial variability and correlations between sampling points, allowed characterizing the average SOC stock at PP through the cumulative value per average area unit, which was 8.5 kg m^{-2} and somewhat higher compared to the value of 7.3 kg m^{-2} obtained by simply averaging the 70 sampling points only (PP1 in Fig. 3). In contrast, the lack of spatial structure at the investigated scale at NF, despite the intense sampling scheme, can be attributed to inherent variability at scale shorter than the measurements, which reflects the heterogeneous spatial pattern of the forest vegetation.

4.2 Comparison with published data

Total SOC at NF was mainly in the 0–55 cm soil mineral layer (13.7 kg m^{-2}) with only a small share in the litter layer (0.5 kg m^{-2}). At PP we observed the absence of the humus layer and a lower SOC content in the 0–55 cm layer (8.5 kg m^{-2}) compared with NF. Contribution of the litter layer to the pre-conversion C stock needs to be included for the quantification of changes in SOC; however, the dynamics of the organic matter decomposition in the litter and in the mineral soil are substantially different, and this must be taken into account in the direct comparison of their OC content.

As a consequence of 37 years of poplar cultivation we found a decrease in SOC of about 40 % compared with the pre-conversion amount (mineral soil and litter layer combined), thus confirming a considerable reduction in SOC stock after transformation of forest to agricultural land use as found in the two meta-analytical reviews of Guo and Gifford (2002) and Poeplau et al. (2011). Guo and Gifford (2002) reported an average

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SOC stock decline of about 50 % in the 0–60 cm layer after land use change from forest to crop. For the same type of conversion Popleau et al. (2011), using an exponential model to describe the temporal dynamic of SOC loss in the mineral soil, obtained a SOC decrease at equilibrium of −32 ± 20 % (±95 % confidence interval) of the initial stock.

The SOC stock of NF with 14.2 kg m^{-2} (0–55 cm) is quite high compared with the average carbon pool of about 4.2 kg m^{-2} (0–20 cm) reported by Baritz et al. (2010) for European forest soils belonging to the pedological type and climate areas comparable with ours, or with 5.0 kg m^{-2} estimated by Arrouays et al. (2001) for the top layer (0–30 cm) of French forests soils of the Regosol type. Instead the SOC stock of our NF is comparable to a stock of 15.8 kg m^{-2} (0–45 cm) found by Ferré et al. (2012) in another semi-natural mixed oak forest on Regosol in Lombardia, Italy.

The intensity of management of our PP is low; soil mould board ploughing to a depth of approximately 55 cm was done every 12–14 years at the start of a cultivation cycle, with annual harrowing (0–15 cm) during the periods of poplar stand providing continuous organic matter input of both leaves and roots. Normal management of poplar plantations in the Po Plain includes regular irrigation and fertilization, the cultivation cycle is 8–10 years, and therefore ploughing is more frequent. Besides, harrowing can be performed more than once a year. Hence, under more intensive management SOC losses even higher than the quantified 40 % could be expected following conversion of natural forest to poplar plantations.

The experimental sites belong to the alluvial valley of the Ticino River, where the river dynamics and the young age of sediments are the reason for the poor evolution of the soils. From a pedological point of view, soils of the two sites are comparable. The differences in soil texture found between the sites as well as the intra-site spatial variability are closely connected to the alluvial sediment deposition dynamics. Soils showed a tendency to a coarser texture in NF compared with the PP site. In regard to this, we identified significant negative correlations between sand content and SOC content and positive correlations with finer particles (data not shown, see Fig. 2), in

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line with results given in Yao et al. (2010). The lower sand content at PP at similar SOC of the C-horizon therefore let us assume that pre-conversion SOC content was even higher than at the NF site. Moreover, when it was possible to compare soils with similar soil texture, we observed an increase in SOC losses higher than 40 % (Fig. 3) for soils with high coarse sand content; our estimate for changes in SOC stock as a consequence of land use conversion from forest to poplar are therefore likely to be conservative.

4.3 Application of the IPCC method for the calculation of SOC changes due to land use conversion

In providing general rules for reporting of carbon stock changes due to land use, land use change and forestry (LULUCF), IPCC (2006) gives default SOC stocks for a climatic/edaphic situation comparable to ours (high activity clay soil, tree crop-full tillage-low input, cool/warm temperate moist climate) of 92 t ha^{-1} for the native forest and of 84 t ha^{-1} SOC stock after the land use conversion to tree crop. The corresponding variation of −8 % appears to be much too low compared to our measurements. IPCC (2006) assumes that forests above 30 % canopy cover are excluded from conversion to cropland; thus, considering mature forest with less than 30 % cover as prior land use probably resulted in an underestimation of the reference organic carbon content. On the other side, the IPCC method refers to SOC in the mineral topsoil layer 0–30 cm only, which is considered the common thickness of ploughed horizons. Since the depth taken into account can significantly affect estimates of total SOC, it would be more appropriate to consider a cautionary deeper sampling limit in order to properly describe the effects of land use change on soil C stock. Anyhow, for a hypothetical soil depth of 30 cm, the difference in SOC stock between our sites would become 57 % instead of 40 %.

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4.4 Other soil changes due to land use conversion

The conversion of a forested soil to cultivated land usually comes with a decrease in the addition of organic matter; at the same time the characteristics of added organic matter changes. The production of leaf biomass in a poplar stand, at least in the first part of the cycle, is lower than in a mature natural wood: the average Leaf Area Index (LAI) of an oak wood in a temperate climate is about 5–6 $m^2\,m^{-2}$ (Bréda, 2003), while the LAI of our PP, measured in 2002 when the age of the stand was 12 years, was about 2 (Migliavacca et al., 2009).

Poplar leaves are significantly richer in N, and have a lower C : N ratio than those of common oak, the main tree of the forest site (Table 2). The C : N ratio can be used as a proxy of the organic matter mineralization rate, with respect to which it is inversely related (Berg and Ekbohm, 1983; Zhang et al., 2008). The poplar leaves falling to the ground are mineralized faster than those of common oak: therefore, in the forest site the oak leaves accumulate on the soil surface as litter and their organic matter follows mainly the humification path; on the contrary, poplar leaves do not accumulate on the surface and are quickly mineralized (Cotrufo et al., 2005).

Furthermore, mechanical actions (shredding and mixing) produced by pedofauna and tillage impact carbon turnover in soils. Both ploughing before poplar planting and yearly harrowing enhance soil aeration and consequently SOC mineralization. In addition, the agricultural practices adopted cause the breakdown of aggregates and further increase the degradation processes by exposing organic material to biodegradation and oxidative agents (Elliot, 1986; Six et al., 1999, 2000). As a consequence, a litter layer was lacking at PP, and C : N ratios of mineral soil (0–55 cm) were lower at PP than those at NF. In our study area, Cerli et al. (2009) found differences in fractions of particulate organic matter (POM) connected to conversion of NF to PP; most OM was bound to mineral components at PP, while small amounts were in the free and occluded light fractions, thus suggesting that the periodical disturbances accelerated

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the turnover and disruption of aggregates and therefore the OM mineralization rate, leaving behind only organic material strongly protected against decomposition.

The mineralization rates at PP may be enhanced by higher soil surface temperatures due to sun exposure. For the same study area, the poplar stand studied by Migliavacca et al. (2009) showed a maximum LAI of 2.02, the weedy ground vegetation of *Artemisia vulgaris* and *Poa vulgaris* was regularly removed; whereas LAI of the natural forest ranges around 4–5 and the soil is covered by a thick litter layer. Hence, poplar soil showed higher mean temperatures from May 2002 to November 2003 in the 0–5 cm layer of 15.7 °C, as compared to 14,4 °C at the NF site (Ferré et al., 2005). As a consequence, heterotrophic soil respiration increases (Epron et al., 1999; Rodeghiero and Cescatti, 2005; Ferré et al., 2012).

The conversion from forest to poplar plantation also determined a different distribution of SOC along the profile between the two land uses. The ploughing, carried out before each tree planting at PP, led to the transfer of SOC from soil surface into the deeper layers (Cambardella and Elliott, 1994; Golchin et al., 1994), thus resulting in a more uniform allocation of SOC in the first 55 cm and a disappearance of the SOC stratification observed in the forest.

As for the soil texture, differences in pH_w values between and within the sites, were partly due to the alluvial origin of soils. If pH_w values of the parent materials were similar (Δ pH = 0.5) for the two sites, considerable differences were instead found in the layers affected by the land use change. The rise in the pH_w of the poplar topsoil is not due to the agronomic management, because liming was never done and fertilization was always performed with urea. The improvement of soil pH_w was probably due to the quality of the litter: that of the poplar does not acidify the soil, unlike common oak litter (Nordén, 1994; Hagen-Thorn et al., 2004). Transition of the soil from very acidic (NF) to moderately acidic (PP) reaction could also be due to the mixing activity of soil macrofauna (earthworms are very active in the studied poplar soil) (De Schrijver et al., 2012; Slade and Riutta, 2012), which brings to the surface less acid soil material taken in depth. However, SOC variations were not linked to variations of the pH_w values as demonstrated by the statistical analysis: no significant correlations were found between SOC and pH_w of the parent material (correlation coefficients equal to −0.02 and −0.35 for the NF and the PP site respectively).

5 Conclusion

We studied the effects of forest conversion to poplar plantation on SOC and soil properties in a two paired plot design through a sampling scheme that took into account the heterogeneity of surface and deep soil horizons, which is related to site characteristics and land uses. As commonly observed on young alluvial soils, the soil properties like texture at the neighbouring NF and PP sites showed a high and comparable variability within the site as well as between the sites. For this reason, a dedicated sampling scheme and geostatistical treatment of data was required to quantify the effects of 37 years of poplar cultivation on SOC transfer in depth and the overall stock.

In comparison to the relict forest, at the poplar site the litter layer was lost and the carbon stock in the 0–55 cm layer of the mineral soil was depleted by 5.7 kg m^{-2} resulting in an overall SOC decrease of about 40 % in total or of 1 % per year. Considering soils with sand content higher than 56 %, the SOC loss became more pronounced, reaching 61 %. For a soil depth of 30 cm as considered in IPCC reporting, the SOC loss in our study with −57 % was almost an order of magnitude higher compared to the IPCC value of −8 % to be considered for a corresponding land use change

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References

Arrouays, D., Deslais., W., and Badeau, V.: The carbon content of top soil and its geographical distribution in France, Soil Use Manage., 17, 7–11, 2001.

Baize, D. and Girard, M. C. (Eds.): Référentiel pédologique, Quae, Versailles, France, 2008.

Baldock, J. A.: Composition and cycling of organic carbon in soil, in: Nutrient Cycling in Terrestrial Ecosystems, edited by: Marschner, P. and Rengel, Z., Springer-Verlag, Heidelberg, Germany, 1–35, 2007.

Baritz, R., Seufert, G., Montanarella, L., and Van Ranst, E.: Carbon concentrations and stocks in forest soils of Europe, Forest Ecol. Manag., 260, 262–277, 2010.

Berg, B. and Ekbohm, G.: Nitrogen immobilization in decomposing needle litter at variable carbon : nitrogen ratios, Ecology, 64, 63–67, 1983.

Bohn, U., Neuhäusl, R., Gollub, G., Hettwer, C., Neuhäuslová, Z., Raus, Th., Schlüter, H., and Weber, H.: Map of the Natural Vegetation of Europe, Scale 1 : 2 500 000, Bundesamt für Naturschutz, Bonn, Germany, 2003.

Bréda, N. J. J.: Ground-based measurements of leaf area index: a review of methods, instruments and current controversies, J. Exp. Bot., 54, 2403–2417, 2003.

Buttafuoco, G. and Castrignanò, A.: Study of the spatio-temporal variation of soil moisture under forest using intrinsic random functions of order k, Geoderma, 128, 208–220, 2005.

Cambardella, C. A. and Elliott, E. T.: Carbon and nitrogen dynamics of soil organic-matter fractions from cultivated grassland soils, Soil Sci. Soc. Am. J., 58, 123–130, 1994.

Cerli, C., Celi, L., Bosio, P., Motta, R., and Grassi, G.: Effect of land use change on soil properties and carbon accumulation in the Ticino Park (North Italy), Studi Trent. Sci. Nat., 85, 83–92, 2009.

COM(2006)232: Proposal for a Directive of the European Parliament and the Council Establishing a Framework for the Protection of Soil and Amending Directive 2004/35/EC, Commission of the European Communities, Brussels, Belgium, 2006.

Cotrufo, M. F., De Angelis, P., and Polle, A.: Leaf litter production and decomposing in a poplar short-rotation coppice exposed to free air CO_2 enrichment (POPFACE), Glob. Change Biol., 11, 971–982, 2005.

De Schrijver, A., De Frenne, P., Staelens, J., Verstraeten, G., Muys, B., Vesterdal, V., Wuyts, K., Van Nevel, L., Schelfhout, S., De Neve, S., and Verheyen, K.: Tree species traits cause divergence in soil acidification during four decades of postagricultural forest development, Glob. Change Biol., 18, 1127–1140, 2012.

Ellert, B. H. and Bettany, J. R.: Calculation of organic matter and nutrients stored in soils under contrasting management regimes, Can. J. Soil Sci., 75, 529–538, 1995.

Elliott, E. T.: Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils, Soil Sci. Soc. Am. J., 50, 627–633, 1986.

Epron, D., Farque, L., Lucot, E., and Badot, P. M.: Soil CO_2 efflux in a beech forest: dependence on soil temperature and soil water content., Ann. For. Sci., 56, 221–226, 1999.

Ferré, C., Leip, A., Matteucci, G., Previtali, F., and Seufert, G.: Impact of 40 years poplar cultivation on soil carbon stocks and greenhouse gas fluxes, Biogeosciences Discuss., 2, 897–931, doi:10.5194/bgd-2-897-2005, 2005.

Ferré, C., Zenone, T., Comolli, R., and Seufert, G.: Estimating heterotrophic and autotrophic soil respiration in a semi-natural forest of Lombardy, Italy, Pedobiologia, 55, 285–294, 2012.

Golchin, A., Oades, J. M., Skjemstad, J. O., and Clarke, P.: Study of free and occluded organic matter in soils by ^{13}C CP/MAS NMR spectroscopy and scanning electron microscopy, Aust. J. Soil Res., 32, 285–309, 1994.

Guo, L. B. and Gifford, R. M.: Soil carbon stocks and land use change: a meta-analysis, Glob. Change Biol., 8, 345–360, 2002.

Hagen-Thorn, A., Callesen, I., Armolaitis, K., and Nihlgard, B.: The impacts of six European tree species on the chemistry of mineral topsoil in forest plantations on former agricultural land, Forest Ecol. Manag., 195, 373–384, 2004.

Houghton, R. A.: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, Tellus, 55, 278–390, 2003.

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11, 9601–9627, 2014

Forest conversion to poplar plantation

C. Ferré et al.

Houghton, R. A.: Historic changes in terrestrial carbon storage, in: Recarbonization of the Biosphere – Ecosystems and the Global Carbon Cycle, edited by: Lal, R., Lorenz, K., Hüttl, R. F., Schneider, B. U., and von Braun, J., Springer Verlag, Heidelberg, Germany, 59–82, 2012.

Hurlbert, S. J.: Pseudoreplication and the design of ecological field experiments, Ecol. Monogr., 54, 187–211, 1984.

IPCC (Intergovernmental Panel of Climate Change): Land Use, Land Use Change, and Forestry, Cambridge University Press, Cambridge, England, 2000.

IPCC (Intergovernmental Panel of Climate Change): Good Practice Guidance for Land use, Land-use Change and Forestry, IGES, Hayama, Japan, 2003.

IPCC (Intergovernmental Panel of Climate Change): Revised IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel of Climate Change Publication, Cambridge University Press, Cambridge, England, 2006.

IUSS Working Group WRB: World Reference Base for Soil Resources 2006, first update 2007, World Soil Resources Reports, 103, FAO, Rome, Italy, 2007.

Jenkinson, D. S.: The Accumulation of Organic Matter in Soil Left Uncultivated, Rothamsted Experimental Station Report for 1970, 2, Lawes Agricultural Trust, Harpenden, England, 1971.

Jones, R. J. A., Houšková, B., Bullock, P., and Montanarella, L. (Eds.): Soil Resources of Europe, 2nd edn., Office for Official Publications of the European Communities, Luxembourg, 2005.

Lal, R.: Soil carbon sequestration impacts on global climate change and food security, Science, 304, 1623–1627, 2004.

Matheron, G.: The intrinsic random functions and their applications, Adv. Appl. Probab., 5, 239–465, 1973.

Migliavacca, M., Meroni, M., Manca, G., Matteucci, G., Montagnani, L., Grassi, G., Zenone, T., Teobaldelli, M., Goded, I., Colombo, R., and Seufert, G.: Seasonal and interannual patterns of carbon and water fluxes of a poplar plantation in northern Italy, Agr. Forest Meteorol., 149, 1460–1476, 2009.

Motta, R., Nola, P., and Berretti, R.: The rise and fall of the black locust (*Robinia pseudoacacia* L.) in the "Siro Negri" Forest Reserve (Lombardy, Italy): lessons learned and future uncertainties, Ann. For. Sci., 66, 1–10, 2009.

Murty, D., Kirschbaum, M. U. F., McMurtrie, R. E., and McGilvray, H.: Does conversion of forest to agricultural land change soil carbon and nitrogen?, A review of the literature, Glob. Change Biol., 8, 105–123, 2002.

Nieder, R. and Benbi, D. K.: Carbon and Nitrogen in the Terrestrial Environment, Springer-Verlag, Heidelberg, Germany, 2008.
Nordén, U.: Influence of tree species on acidification and mineral pools on deciduous forest soils of south Sweden, Water Air Soil Poll., 76, 363–381, 1994.
NRCS: Soil Survey Laboratory Methods Manual, Soil Survey Investigations Report, 42, USDA-NRCS, Lincoln, NE, USA, 2004.
Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., van Wesemael, B., Schumacher, J., and Gensior, A.: Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach, Glob. Change Biol., 17, 2415–2427, 2011.
Ravazzi, C., Marchetti, M., Zanon, M., Perego, R., Quirino, T., Deaddisa, M., De Amicis, M., and Margaritora, D.: Lake evolution and landscape history in the lower Mincio River valley, unravelling drainage changes in the central Po Plain (N-Italy) since the Bronze Age, Quatern. Int., 288, 195–205, 2013.
Rodeghiero, M. and Cescatti, A.: Main determinants of forest soil respiration along an elevation/temperature gradient in the Italian Alps, Glob. Change Biol., 11, 1024–1041, 2005.
Six, J., Elliott, E. T., and Paustian, K.: Aggregate and soil organic matter dynamics under conventional and no-tillage systems, Soil Sci. Soc. Am. J., 63, 1350–1358, 1999.
Six, J., Merckx, R., Kimpe, K., Paustian, K., and Elliott, E. T.: A re-evaluation of the enriched labile soil organic matter fraction, Eur. J. Soil Sci., 51, 283–293, 2000.
Slade, E. M. and Riutta, T.: Interacting effects of leaf litter species and macrofauna on decomposition in different litter environments, Basic Appl. Ecol., 13, 423–431, 2012.
Tomaselli, R. and Gentile, S.: La riserva naturale integrale“Bosco Siro Negri” dell’Università di Pavia, Atti Ist. Lab. Critt. Univ. Pavia, 7, 41–70, 1971.
Webster, R.: Analysis of variance, inference, multiple comparisons and sampling effects in soil research, Eur. J. Soil Sci., 58, 74–82, 2007.
Wendt, J. W. and Hauser, S.: An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers, Eur. J. Soil Sci., 64, 58–65, 2013.
Yao, M. K., Angui, P. K. T., Konate, S., Tondoh, J. E., Tano, Y., Abbadie, L., and Benest, D.: Effects of land use types on soil organic carbon and nitrogen dynamics in Mid-West Cote d’Ivoire, Eur. J. Sci. Res., 40, 211–22, 2010.
Zhang, D., Hui, D., Luo, Y., and Zhou, G.: Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors, J. Plant Ecol.-UK, 1, 85–93, 2008.

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Table 1. Summary of results of organic layer and coring of mineral soils at NF ($n = 90$) and PP sites ($n = 70$): average and standard error (SE) of SOC, C : N ratio, bulk density, pH_w, sand, silt and clay content. Soil texture $n = 20$ for the third layer 55–100 cm. L: organic layer.

Site	Layer	SOC [g kg^{-1}] average	SE	C : N average	SE	bulk density [g cm^{-3}] average	SE	pH_w average	SE	Sand 2–0.05 mm % average	SE	Silt 0.05–0.002 mm % average	SE	Clay < 0.002 mm % average	SE
NF	L	380.3	6.27	19.2	0.27										
	1 (0–10 cm)	51.5	2.44	13.4	0.09	0.99	0.01	4.6	0.05	59.9	2.12	36.9	1.94	3.2	0.25
	2 (10–55 cm)	20.3	0.75	13.2	0.09	1.28	0.01	4.7	0.04	69.6	1.45	26.0	1.31	4.4	0.18
	3 (55–100 cm)	3.3	0.18	14.5	0.40	1.51	0.01	5.3	0.04	84.2	1.18	13.7	1.08	2.1	0.12
PP	1 (0–15 cm)	11.1	0.42	10.9	0.1	1.21	0.01	5.9	0.02	46.7	0.21	47.4	0.20	5.9	0.28
	2 (15–55 cm)	9.7	0.36	10.5	0.21	1.22	0.01	5.7	0.03	46.9	0.22	47.1	0.20	6.0	0.29
	3 (55–100 cm)	3.8	0.11	9.3	0.11	1.33	0.03	5.7	0.06	51.0	0.25	43.4	0.23	5.5	0.29

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Table 2. Tree leaves ($N = 5$): content of organic carbon (OC) and total nitrogen (N) and C : N ratio.

Species	OC (%)	Total N (%)	C : N
Acer campestre	42.59 ± 0.86	1.01 ± 0.03	42.2 ± 1.4
Corylus avellana	49.51 ± 1.25	1.65 ± 0.07	30.1 ± 1.6
Populus x euroamericana	47.95 ± 1.28	1.48 ± 0.05	32.3 ± 1.5
Quercus robur	48.24 ± 1.81	0.96 ± 0.05	50.3 ± 2.8
Robinia pseudacacia	44.28 ± 0.44	3.00 ± 0.02	14.8 ± 0.4

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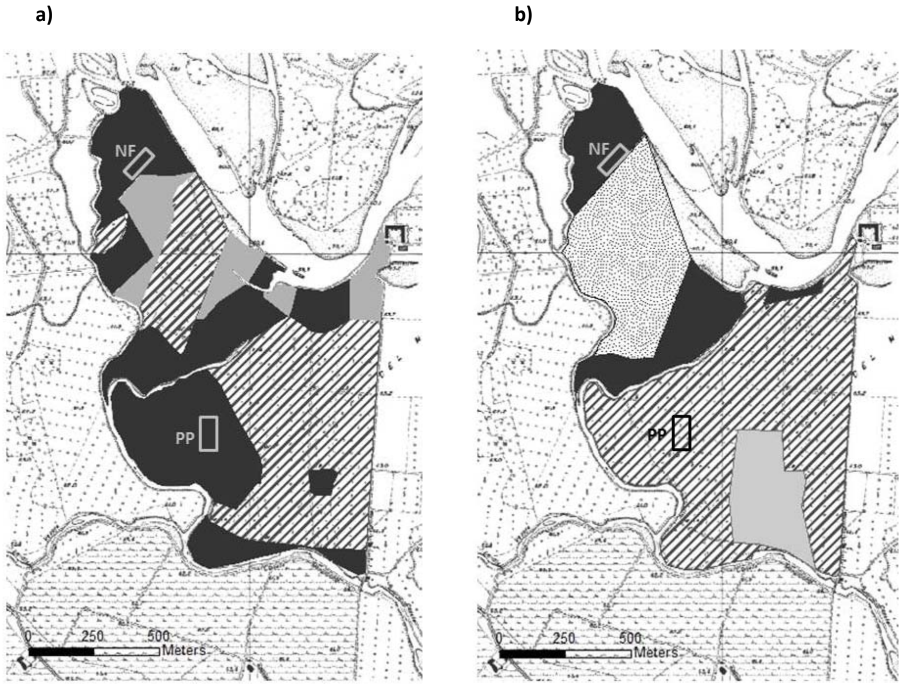

Figure 1. Land use of the study area in 1954 **(a)** and 2007 **(b)**. (Natural forest: NF; poplar plantation: PP). Land use type: forest (black area), poplar plantation (lined area), cropland (grey area), recent afforestation (dotted area).

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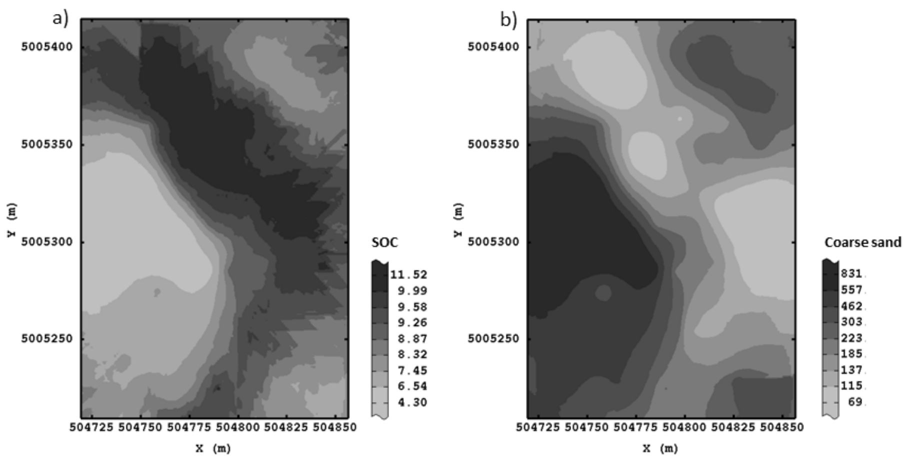

Figure 2. Spatial estimates of **(a)** SOC stock (kg m^{-2}) and **(b)** coarse sand content (g kg^{-1}) of the 0–55 cm layer at the PP site. The grey scale represents isofrequency classes.

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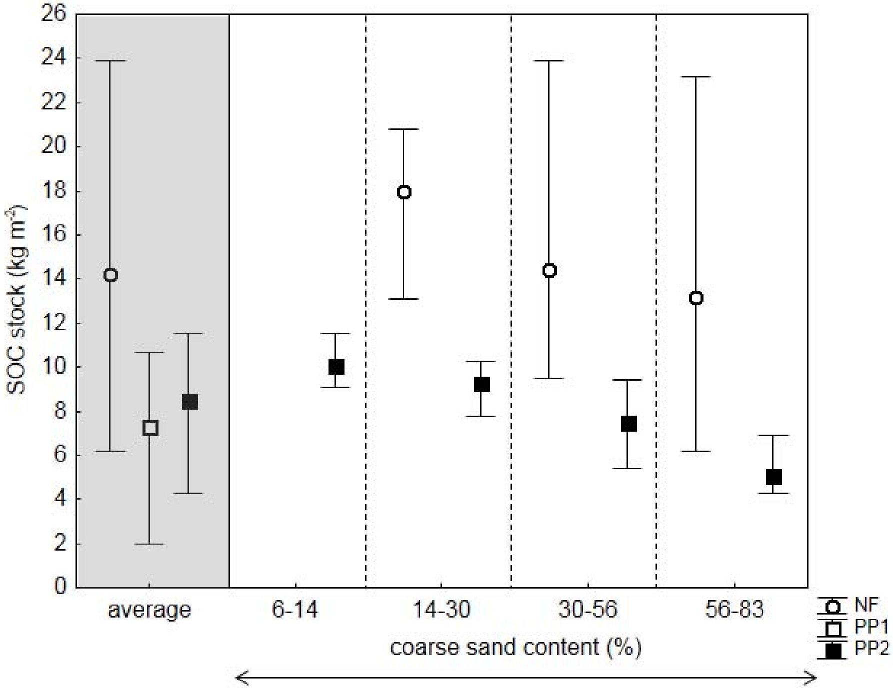

Figure 3. Average SOC stock (kg m^{-2}) of the 0–55 cm layer at the NF and the PP sites and SOC values relative to various content of coarse sand (from soil coring, mass corrected). NF: results are given as average (n = 90) and range of variation (minimum value – maximum value); PP1: results are given as average (n = 70) and range of variation (minimum value – maximum value); PP2: results are given as cumulative value per area unit and range of variation (minimum value – maximum value)