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Changes in soil organic carbon and nitrogen following forest expansion on grassland in the Southern Alps

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ABSTRACT

The dominant land-use change in the Southern Alps is grassland abandonment, followed by forest expansion. Forest expansion is commonly thought to increase ecosystem C sequestration, but contradictory results have been reported. Our objective was to investigate soil organic carbon (SOC) and nitrogen (N) changes after forest expansion on abandoned grasslands. A land use and management gradient was identified in a subalpine area of Trentino (Italy) comprising four successional stages: (i) managed grassland (manG), mown and manured annually for more than 100 years; (ii) grassland abandoned 10 years ago (abanG), with shrubs and *Picea abies* saplings; (iii) early-stage forest (earlyF), dominated by *P. abies* established on grassland abandoned around 1970; and (iv) old forest (oldF), dominated by *Fagus sylvatica* and *P. abies*, representing a reference for long-term forest land use. Organic and mineral soil layers were collected down to 30 cm at eight points within three plots for each successional stage.

Significantly more SOC was stored in organic layers of oldF compared with other successional stages and the organic layer N stocks were higher in oldF compared with manG and abanG. The SOC and N concentrations were higher in the top 10 cm mineral soil of grassland plots compared with forest. The earlyF and oldF stored, on average, 28–35% less SOC in top 10 cm mineral soil compared with manG and abanG when stocks were calculated using equivalent soil mass (ESM) and equivalent soil depth (ESD) approaches respectively. SOC stocks in mineral soil (0–30 cm) calculated with ESD decreased from manG to oldF; when accounting for total stone content, SOC stocks in earlyF and oldF were 40% and 50% lower than in manG, respectively. The inclusion of organic layers offset mineral SOC stock differences when only stones <5 cm were accounted for, but when considering the total stone content, SOC stocks in earlyF remained significantly lower (−31%) than in manG. Tree biomass contributed to higher ecosystem C stocks in oldF, which stored 82–93 Mg ha^{-1} of C more than grasslands.

Our study revealed a decrease in total SOC stocks after forest expansion on abandoned subalpine grasslands. Tree biomass development contributed to increasing C storage, especially in a long-term forest land use. Forest management should consider that tree biomass and organic layer development require a minimum time period following grassland abandonment to compensate for the decrease in mineral SOC stocks and contribute positively to climate change mitigation.

1. Introduction

Land-use change (LUC) plays a major role in global carbon (C) budgets, influencing the amount of C stored both in vegetation and soil (Foley et al., 2005). Soil organic carbon (SOC) stocks are controlled by the balance between C inputs and outputs from soils, and LUC may influence C input as well as output fluxes from ecosystems (Guo and Gifford, 2002). Changes in SOC stocks can be harder to detect than changes in aboveground plant biomass (Post et al., 2001) but cannot be overlooked since soil C dynamics can alter predictions of total ecosystem C storage (Jackson et al., 2002). Changes in SOC stocks resulting from LUC can be better explained if nitrogen (N) changes are also taken into account (Halliday et al., 2003), given the close link between C and N in soil organic matter (SOM) pools.

Abbreviations: manG, managed grassland; abanG, abandoned grassland; earlyF, early-stage forest; oldF, old forest; ESD, equivalent soil depth; ESM, equivalent soil mass.

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Recently, large areas of agricultural land have been abandoned worldwide, such as in Europe (Fuchs et al., 2013), East Asia (Zhang et al., 2010), eastern North America (Brown et al., 2005) and South America (Grau and Aide, 2008). The abandonment of grasslands represents the dominant LUC pattern and the main driver for the establishment of new forest areas in mountainous and subalpine regions of Europe (Zimmermann et al., 2010). Land abandonment can be explained by a series of socio-economic changes, which lead to agricultural specialization/intensification in the most fertile areas, whereas unproductive and less accessible sites are abandoned (Tappeiner et al., 2008). As a consequence of grassland abandonment, progressive forest expansion commonly takes place, especially where site conditions and biotic factors are favorable (Haugo et al., 2013).

The expansion of forests on grasslands is widely thought to act as a C sink, which has mainly been based on the obvious increase in C stored in aboveground biomass after forest establishment on grassland (Risch et al., 2008), while changes in SOC stocks are uncertain (Schulze et al., 2009; Poeplau and Don, 2013). The direction and magnitude of SOC changes can be affected by a multitude of factors such as climate, management history, tree species colonizing the grassland, soil type, and time since abandonment (Thuille and Schulze, 2006). In some cases, a depletion in SOC stocks can even offset the increase in C stored in plant biomass (Jackson et al., 2002).

Recent reviews have investigated the effect of grassland to forest conversions on SOC, focusing mainly on human-induced afforestation (Laganiere et al., 2010; Poeplau et al., 2011). According to Laganiere et al. (2010), afforestation of pastures and natural grasslands did not result in a significant increase in SOC stocks. Also Poeplau et al. (2011) reported that afforestation of grasslands, in most cases, did not lead to SOC accumulation: in fact 75% of observations showed SOC losses, even up to 100 years following afforestation. Several factors can be responsible for the reduction of C stored in the mineral soil. Firstly, a shift from grassland to forest leads to a change in rooting system: forests are characterized by roots with slower turnover and lower fine root biomass compared with grasslands (Solly et al., 2013), which can lead to a reduced rate of humus formation (Guo et al., 2007). Secondly, forest growth in grassland areas causes a shift in the composition of soil fauna, with the development of a new fauna that is often less capable of transferring the aboveground C input into the mineral soil (Seeber et al., 2005). However, losses of SOC in the mineral soil can be counterbalanced through the build-up of organic layers, which accumulate over time until a steady state condition between litterfall and decomposition is reached (Hooker and Compton, 2003; Thuille and Schulze, 2006). The SOC stored in the organic layers, however, responds faster to changes in environmental conditions and management than SOC in the mineral layers (Gaudinski et al., 2000). Furthermore, the conversion from grassland to forest was shown to decrease mineral SOC storage in stable aggregates while increasing particulate organic matter accumulation, thus suggesting an overall decrease in physical stability of total SOC stocks (Poeplau and Don, 2013).

Natural forest expansion on abandoned grasslands may have a different impact on SOC storage than human-induced afforestation. With afforestation, initial losses of SOC can be stimulated by site preparation prior to tree planting, but this is absent in the process of natural forest expansion (Poeplau et al., 2011). Site preparation can affect SOC through increased organic matter (OM) mineralization and via the removal of grassland vegetation, thereby reducing net primary productivity and fine root input in the first years following afforestation (Don et al., 2009). On the other hand, canopy cover occurs later and with higher spatial variation after natural forest expansion compared with the establishment of plantations. The LUC can consequently take more time and therefore a longer period of time will be needed to detect a change in SOC stocks.

Especially in cold and mountainous regions, OM dynamics are still unclear (Leifeld and Fuhrer, 2009). In temperate and boreal regions, OM turnover is slower compared with tropical regions (Trumbore, 1993), and the balance between input and output from soils takes a longer time to establish (Olson, 1963). Carbon accumulation consequently lasts longer in cold than in warm regions (Laganiere et al., 2010), and C sink saturation after LUC can take more than 100 years (Poeplau et al., 2011). Changes in SOC following LUC in mountainous regions can therefore be expected to occur at lower rates compared with warmer lowland regions. Despite the recent and current increase in forest area due to grassland abandonment, only few studies have investigated its effect on SOC stocks.

Contrasting trends in SOC storage have been reported for mountainous regions following forest expansion in abandoned grasslands. A decrease in mineral SOC stocks after forest expansion was shown by Thuille et al. (2000) and Thuille and Schulze (2006) in the case of coniferous forest expansion in the Italian Alps and Germany, and by Alberti et al. (2008) for deciduous forest expansion in the Italian Prealps. However, other studies have reported an increase or no change in mineral SOC stock, such as after shrub encroachment into mountain grasslands of the Iberian peninsula (Montane et al., 2007) and conifer forest development in the Swiss Alps (Risch et al., 2008). In Trentino, a mountainous region of the Southern Alps (Italy) where 55% of the total land (6207 km^2) is currently occupied by forests (Rodeghiero et al., 2010), the forest area increased by 5% from 1973 to 1999, mainly due to natural forest expansion on previous grasslands (Sitzia, 2009). In our study, a typical case of forest expansion for that region was selected based on the "Neoboschi" project (2002–2005) (Sitzia, 2009). A land use and management gradient was identified at the selected study area, comprising managed grassland, old mixed forest, and two transitional phases where abandonment of grasslands led to progressive forest colonization. The objective of this study was to investigate changes in SOC and N stocks after forest expansion on alpine grasslands. Our specific aims were to: (i) compare SOC, N concentrations and C/N ratio in mineral and organic layers, and (ii) compare SOC and N stocks in the mineral and organic layers of managed grassland, old mixed forest, and transitional phases.

2. Materials and methods

2.1. Study area

The Neoboschi project investigated forest expansion in Trentino (Southern Alps, Italy), through the comparison of aerial photos taken in 1973 and 1999 and via field surveys (Sitzia, 2009). The forest expansion areas are dominated by tree and shrub species: Norway spruce (*Picea abies* (L.) Karst.), Common hazel (*Corylus avellana* L.), Green alder (*Alnus viridis* (Chaix.) D.C.), European larch (*Larix decidua* Mill.), and Hop-hornbeam (*Ostrya carpinifolia* Scop.) (Sitzia, 2009). Recently expanded forests examined by the Neoboschi project have the following common features: (i) developed by natural regeneration; (ii) established on previous meadows or pastures; (iii) located at an elevation of around 600–1200 m a.s.l; and (iv) located on south-facing gentle slopes.

Our study area was selected among the areas identified by the Neoboschi project, ensuring that all four common characteristics were included. This allowed us to investigate a forest expansion pattern typical for Trentino. The study area (45.94584 N, 11.25148 E) was located in a mountainous region in the municipality of Lavarone (Trentino, Italy), with an elevation of around 1150 m a.s.l (Fig. 1). In the period 1992–2011, the mean annual air