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40 years of succession or mulching of abandoned grassland affect phosphorus fractions in soil

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ABSTRACT

Grazing and mowing commonly form part of agricultural management. Nowadays, these grassland management measures – complemented by low-cost treatments such as mulching – often aim at keeping the rural landscape open and at avoiding natural succession. The evaluation of these treatments has not yet accounted for the long-term perspective particularly important for soil phosphorus (P).

In a four-decade long experiment in Southwestern Germany, the effects of mulching and natural succession on labile, moderately labile, and stable inorganic (Pi) and organic (Po) P fractions in soil of six sites (three in the Black Forest and three at the Swabian Alb) were studied. Our objectives were to test i) the effect of mulching or natural succession on P fractions in soil, and ii) whether the temporal development of P fractions in soil differs among mulching treatments and natural succession up to 40 years after abandonment of former land use. Special emphasis was paid to differences in bedrock combined with water regime.

Soils developed on non-calcareous bedrock showed higher labile Po concentrations as compared to those developed on calcareous bedrock caused by reduced decomposition induced by water saturation and low quality of plant material. The normalization of P fractions to the respective site average revealed that mulching twice a year reduced concentrations of labile and moderately labile Pi, stable and total P in soil likely attributable to vertical transport of Pi. Comparing soil P fractions in 2014 to those of archived samples of 1975, succession resulted in a decrease in labile P fractions and increase in stable P fractions over time which could be explained by processes during soil development. Such processes were less pronounced in the mulching treatment indicating that decomposition of mulching material contributes to maintain P nutrition. In conclusion, mulching can be recommended as it contributes to maintaining P fractions bioavailable while at the same time promoting P limiting conditions.

1. Introduction

In recent years it has become apparent that phosphorus (P) limitation of primary producers is much more widespread in terrestrial ecosystems than previously thought (Vitousek et al., 2010). Phosphorus limitation in ecosystems is expected to increase in the future because of continuously high atmospheric nitrogen deposition (Crowley et al., 2012). Nutritional shifts in particular affect low-input agricultural ecosystems such as semi-natural grasslands. At the same time, these grasslands harbour a great variety of organisms including endangered species relying on comparatively low nutrient availability (Bakker and Berendse, 1999; Liira et al., 2008). Because low-input semi-natural grasslands are threatened either by intensification or cessation of land use (Poschlod et al., 2005), conservation or restoration measures have been initiated aiming at maintaining or establishing species-rich grasslands (Berendse et al., 1992; Eler et al., 2005; Gaisler et al., 2013; Pavlu et al., 2005; Poptcheva et al., 2009; Ryser et al., 1995; Schreiber et al., 2009).

The conservation/restoration success is coupled to nutrient availability in soil (Bakker and Berendse, 1999; Bakker et al., 2002; Oelmann et al., 2009; Pavlu et al., 2016). For P, the bioavailability in soil is difficult to capture since P in soil comprises labile, moderately labile, and stable organic and inorganic fractions. These are commonly extracted with increasingly aggressive alkaline and acidic solutions (Cross and Schlesinger, 1995; Hedley

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et al., 1982; Negassa and Leinweber, 2009). Labile organic P (Po) and inorganic P (Pi) fractions are considered to be readily available to plants although the classification of moderately labile P fractions as non-readily bioavailable has raised some debate (Oelmann et al., 2011; Pätzold et al., 2013). Soil pH represents a strong control of labile Pi i.e., dissolved phosphate ($H_2PO_4^-$/HPO_4^{2-}) because of the pH-dependent dissolution equilibrium of Ca- (high pH) and Al/Fe- (low pH) containing phosphate minerals. Therefore, soils developed on calcareous bedrock with high pH are expected to have lower labile Pi concentrations as compared to soils developed on non-calcareous bedrock with low pH (McKenzie and Bremer, 2003; Tyler, 2002). For Po, contrasting results were published: i) soil pH had a minor influence on Po concentrations in a grassland soil (Turner and Blackwell, 2013) and ii) low pH increased labile Po concentrations in arable soils (McKenzie and Bremer, 2003). Reduced microbial activity and associated decomposition rates under acidic conditions might explain the relative accumulation of labile Po. Because labile P fractions are replenished by more strongly bond P fractions (Cross and Schlesinger, 1995; Richter et al., 2006), differences between soils developed on calcareous or non-calcareous bedrock might apply for moderately labile and stable P fractions as well. Other factors like water regime might further influence P fractions in soil (Rubio et al., 1995).

Management measures in grasslands, such as application of organic and inorganic fertilizers, grazing, mowing and subsequent hay removal were reported to influence the contributions of labile, moderately labile, and stable P fractions in soil (Alt et al., 2011; Pätzold et al., 2013). In these studies, organic and inorganic P fractions were closely linked: inorganic P fertilizer not only increased Pi but also labile and stable Po fractions. All studies published so far on effects of management measures on soil P fractions in grasslands have major inputs (fertilization) and outputs (removal of harvest) in common. In contrast, less intensive management measures dedicated to maintain species-rich grasslands omit fertilization because of the negative relationship between nutrient availability in soil and plant species richness (Janssens et al., 1998). Whether or not hay removal is beneficial for plant species richness depends on nutrient availability in soil: hay removal without compensation by fertilizers results in i) impoverishment of nutrient-rich sites potentially promoting the establishment of species-rich grasslands (Berendse et al., 1992; Jacquemyn et al., 2003; Pegtel et al., 1996; Walker et al., 2004), or ii) degradation of nutrient-poor sites posing problems to successful establishment/maintenance of species-rich grasslands (Oelmann et al., 2009; Van Duren et al., 1997). As hay removal is not recommended for the latter case and as it is economically costly, alternative measures such as mulching have been tested (Dolezal et al., 2011; Moog et al., 2002; Pavlu et al., 2016). Mulching consists of cutting the grassland vegetation aboveground, chopping the organic material into small pieces and leaving this material as a thin layer on top of the cut vegetation (Moog et al., 2002; Schiefer, 1981; Schreiber et al., 2009). In this way, mulching promotes grassland-internal nutrient cycling comprising decomposition of mulching material, associated nutrient release and subsequent nutrient uptake by plants and soil organisms. Such tight cycling prevents auto eutrophication, a process which was observed if natural succession took place in calcareous grasslands (Moog et al., 2002). However, if low temperature (e.g., at higher altitudes) or high moisture (e.g., in temporarily water-saturated soils) hampers decomposition of mulched material, auto eutrophication might occur (Dolezal et al., 2011).

Studies on the effectiveness of management measures in terms of nutrient cycling aiming at maintaining species-rich grasslands have focused on intermediate periods of time appropriate for revealing changes in plant composition and nutrients with comparatively fast dynamics e.g., N and potassium (Oelmann et al., 2009; Pavlu et al., 2013; Uhlirova et al., 2005). Interpretations on P dynamics in these studies suffer from i) potential legacy effects of former land use (including fertilization of grasslands; Smits et al., 2008; MacDonald et al., 2012), and ii) slow dynamics and responsiveness to management measures because of the strong physico-/geochemical control of labile P fractions in soil (Negassa and Leinweber, 2009; Walker and Syers, 1976). Therefore, an extended duration of experimental treatments is necessary to provide robust evidence for effects of management measures on P fractions in soil. At these time scales, two controlling processes might interact with yet unknown outcome. First, decadal time scales after a shift in land use (arable land to forest) were associated with redistributions in soil P fractions in favour of organic P cycling–not necessarily affecting labile Pi concentrations in soil (Brandtberg et al., 2010; De Schrijver et al., 2012; Richter et al., 2006). Second, total P concentrations along with labile Pi availability in soil decrease with ongoing pedogenesis (Turner and Condron, 2013; Walker and Syers, 1976). The shift in land use from traditional grassland management (50 years ago, no fertilizer) to mulching or succession is not associated with pronounced changes in soil pH – due to the buffer capacity of the soils under study – or soil organic matter (SOM) concentrations (Schreiber et al., 2009) as was the case for the above-mentioned afforestation studies. Therefore, it remains unclear whether effects of management measures predominate over effects originating from pedogenesis at decadal time scales.

Our objectives were to test i) the effect of mulching or natural succession on P fractions in soil, and ii) whether the temporal development of P fractions in soil differs among mulching treatments and natural succession up to 40 years after abandonment of former land use. Special emphasis was paid to differences in bedrock combined with water regime.

2. Methods

2.1. Study regions

We studied six grassland sites, which are part of long-term study sites ("Offenhaltungsversuche", landscape management experiments, Schreiber et al., 2009) in Baden-Württemberg, SW Germany. Plättig, Ettenheimmünster, and Bernau are located in the Black Forest, Hepsisau, Melchingen, and St. Johann at the Swabian Alb. Climatic conditions differ among sites (Table 1). Soils at the sites in the Black Forest developed on granitic bedrock, whereas soils at the Swabian Alb cover Jurassic bedrock (Table 1, S1).

Prior to the establishment of the experiment in 1975, all sites were used as grasslands i.e., either as pasture (Bernau, Hepsisau, St. Johann) or meadow (Plättig, Ettenheimmünster, Melchingen; Schiefer, 1981). Before the start of the long-term experiments, both grassland types received no or small amounts of mineral fertilizer and pastures were grazed by sheep and cattle. In 1975, the sites were divided into plots (100–1400 m^2) with different management practices i.e., mulching and natural succession (US). At each site, treatments were realized in one plot (six sites x three treatments, total n = 18). Mulching comprised two treatments: mulching twice every year (2M) in June and August and mulching every second year in August (M2). Technically, plant material is cut above the soil surface by means of a vertical mulcher, chopped into small pieces and distributed as a thin layer on top of the surface for all mulching treatments. Based on the mass of material being mulched (mean of the years 2006–2014) and the P concentrations of the harvested material in 2015 (regrettably not available for other recent years), the mass of P being recycled for the each of the sites on average was as follows (in g P m^{-2}): Hepsisau 2M: 0.59, M2: 0.24; Melchingen 2M: 0.81, M2: 0.42; St. Johann 2M: 0.50, M2: 0.27; Plättig 2M: 0.67, M2: 0.28;