

Long-term organic phosphorus mineralization in Spodosols under forests and its relation to carbon and nitrogen mineralization

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ABSTRACT

In forest soils where a large fraction of total phosphorus (P) is in organic forms, soil micro-organisms play a major role in the P cycle and plant availability since they mediate organic P transformations. However, the correct assessment of organic P mineralization is usually a challenging task because mineralized P is rapidly sorbed and most mineralization fluxes are very weak. The objectives of the present work were to quantify in five forest Spodosols at soil depths of 0–15 cm net mineralization of total organic P and the estimated increase in plant available inorganic P and to verify whether net or gross P mineralization could be determined using the C or N mineralization rates. Net mineralization of total organic P was derived from the net changes in microbial P and gross mineralization of P in dead soil organic matter. We studied very low P-sorbing soils enabling us to use lower extractants to assess the change in total inorganic P as a result of gross mineralization of P in dead soil organic matter. In addition, to enable detection of gross mineralization of P in dead soil organic matter, a long-term incubation (517 days) experiment was carried out. At the beginning of the experiment, total P contents of the soils were very low (19–51 $\mu\text{g g}^{-1}$) and were essentially present as organic P (17–44 $\mu\text{g g}^{-1}$, 85–91%) or microbial P (6–14 $\mu\text{g g}^{-1}$; 24–39%). Conversely, the initial contents of inorganic P were low (2–7 $\mu\text{g g}^{-1}$; 9–15%). The net changes in the pool size of microbial P during the 517 days of incubation (4–8 $\mu\text{g g}^{-1}$) and the amounts of P resulting from gross mineralization of dead soil organic matter (0.001–0.018 $\mu\text{g g}^{-1} \text{ day}^{-1}$; 0.4–9.5 $\mu\text{g g}^{-1}$ for the entire incubation period) were considerable compared to the initial amounts of organic P and also when compared to the initial diffusive iP fraction (<0.3 $\mu\text{g g}^{-1}$). Diffusive iP corresponds to the phosphate ions that can be transferred from the solid constituents to the soil solution under a gradient of concentration. Net mineralization of organic P induced an important increase in iP in soil solution (0.6–10 $\mu\text{g g}^{-1}$; 600–5000% increase) and lower increases in diffusive iP fractions (0.3–5 $\mu\text{g g}^{-1}$; 300–2000% increase), soil solid constituents having an extremely low reactivity relative to iP. Therefore, soil micro-organisms and organic P transformations play a major role in the bioavailability of P in these forest soils. In our study, the dead soil organic matter was defined as a recalcitrant organic fraction. Probably because gross mineralization of P from this recalcitrant organic fraction was mainly driven by the micro-organisms' needs for energy, the rates of gross mineralization of C, N and P in the recalcitrant organic fraction were similar. Indirect estimation of gross mineralization of P in dead soil organic matter using the gross C mineralization rate seems thus an alternative method for the studied soils. However, additional studies are needed to verify this alternative method in other soils. No relationships were found between microbial P release and microbial C and N releases.

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1. Introduction

Plant roots take up phosphorus (P) essentially as phosphate ions (iP) from the soil solution. In turn, the replenishment of iP in the

soil solution is governed by various physico-chemical and biological processes (Frossard et al., 2000; Hinsinger, 2001; Morel, 2002). Even though many studies have shown the preponderant role of physico-chemical processes in supplying iP for plant nutrition in agricultural cropping systems, some others based on incubation experiments have shown that gross organic P mineralization (1.0–2.5 $\mu\text{g g}^{-1} \text{ day}^{-1}$) could also represent a potentially important

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source of bioavailable P (Achat et al., 2009a; Bünemann et al., 2007; Fardeau, 1996; Morel, 2002; Oehl et al., 2004). Microbial biomass plays an important role in the P cycle and transformations of organic P via excretion of enzymes and mineralization of P in dead soil organic matter, and by acting as a sink (immobilization; incorporation of P into living microbial biomass) or a source (remineralization; release of microbial P after cell death) of bioavailable iP (Achat et al., 2009a; Oberson and Joner, 2005; Oehl et al., 2001, 2004). Furthermore, soil micro-organisms synthesize and liberate organic P (Bünemann et al., 2008). The micro-organisms could thus play a role in organic and inorganic P concentrations in soil solution (Grierson et al., 1998; Seeling and Zasoski, 1993).

The importance of biological processes in the bioavailability of P relative to physico-chemical processes will first of all depend on the sizes of the different P compartments. In particular in soils of ecosystems under permanent vegetation cover (grasslands, forests) organic P forms can make up 50–80% of total P (Achat et al., 2009b; Attiwill and Adams, 1993; Harrison, 1983). The bioavailability of P will thus depend on the mineralization of organic P in such ecosystems (Attiwill and Adams, 1993; Tiessen et al., 1984).

Mineralization of organic P fractions causes a release of iP in soil solution. However, mineralization can only partly be detected by an increase in soil solution iP concentration, because mineralized P is rapidly sorbed onto the soil solid constituents (Frossard et al., 1996). Consequently, mineralization results in an increase in not only rapidly plant available inorganic P, that is, iP in soil solution, but also in diffusive iP (Fig. 1). Diffusive iP corresponds to the phosphate ions

that can be transferred from the solid constituents to the soil solution under a gradient of concentration (Jungk and Claassen, 1997).

Although organic P mineralization could be important in P availability particularly in forests, direct quantification of this flux is extremely difficult since most of mineralized P does not accumulate in solution (Frossard et al., 1996). Consequently, organic P mineralization is rarely studied in forests or other contexts. In general, organic P mineralization can be detected only by isotopic dilution (Achat et al., 2009a; Frossard et al., 1996; Oehl et al., 2001). However, in the case of soils having a weak reactivity towards iP, lower extractants were suggested to adequately extract inorganic P and to correctly assess mineralization of organic P (Grierson et al., 1998, 1999; Polglase et al., 1992). Considering that the strong reactivity of soils towards iP in most conditions will limit the study of organic P mineralization to particular soil contexts or obliges the use of isotopic tools that can be difficult to apply, estimation of organic P mineralization via carbon (C) or nitrogen (N) mineralization rates could represent an interesting and useful indirect approach (Achat et al., 2009b). While there is a common assumption that organic P mineralization is not closely linked to C or N mineralization, up to now C: N: P stoichiometry in the mineralization rates has not been sufficiently studied and verified (McGill and Cole, 1981; Nziguheba and Bünemann, 2005).

The objectives of this study were to i) monitor net microbial P release, gross mineralization of P in dead soil organic matter and therefore kinetics of net mineralization of total organic P (see concept in Fig. 1), ii) quantify the increase in available inorganic P (iP in soil solution and diffusive iP) resulting from net organic P mineralization (Fig. 1), and iii) verify whether C or N mineralization rates could be used to estimate net mineralization of total organic P or gross mineralization of P in dead soil organic matter during an incubation experiment. Therefore, kinetics of net and gross mineralization of C and N were also monitored and compared with net and gross mineralization of organic P. Net C mineralization was determined by the soil respiration and net N mineralization was calculated from the increase in inorganic N extracted with a 1 M KCl solution. Gross C mineralization was calculated from net C mineralization considering a C assimilation by the micro-organisms. This study was carried out using low P-sorbing Spodosols collected from five *Pinus pinaster* forests in a long-term incubation experiment (517 days).

2. Material and methods

2.1. Description of study sites and soils

This study focuses on soil samples collected in March 2007 from five maritime pine (*Pinus pinaster*) stands (VH, VB, TM, TJ, and LB) in the forest range of the 'Landes de Gascogne' in south-western France. Local sites names, geographical coordinates and stand ages are given in Table 1. All the studied stands were planted. VH, VB and LB were not fertilized, while TM and TJ received P fertilizers at plantation (40–80 kg P₂O₅ ha⁻¹; no N applications). All five sites were dry sites with a water table deeper than 2 m from the surface. In this forest range, N and P exportations during a complete stand rotation (40 years) were estimated at 142–732 kg N ha⁻¹ and 7.8–59.2 kg P ha⁻¹ depending on stand management and harvest intensity (L. Augusto, unpublished data).

At each site, the soil collection was done in a zone of 400 m² (20 m × 20 m) using ten randomly chosen sub-zones. Soil was collected from the top mineral soil (0–15 cm) after removing the litter layer. The soil collected from the ten sub-zones was then mixed and homogenized to obtain one composite soil sample per site. In the laboratory, coarse organic debris (roots and/or incorporated above-ground remnants) were removed by sieving over a 4 mm sieve. The moist fresh soil was then stored at 4 °C for a few days prior to the

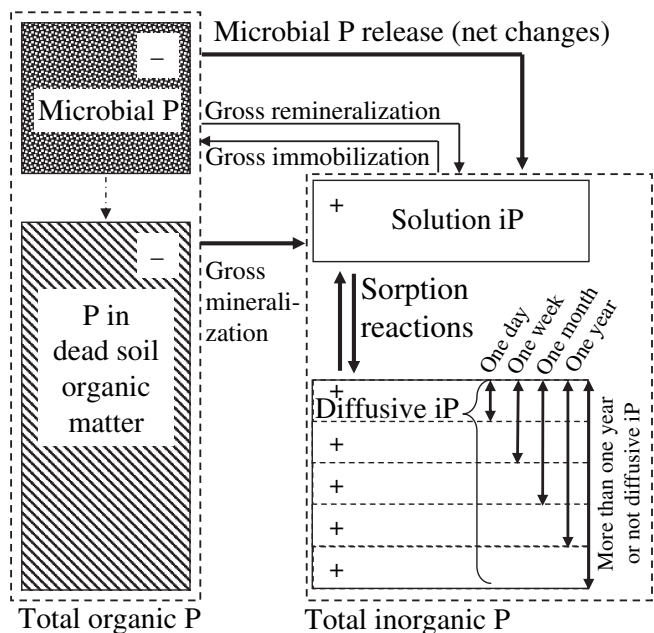


Fig. 1. Conceptual diagram of the phosphorus pools and fluxes assessed during the incubation experiment and of the distribution of mineralized organic P in the different inorganic P pools in the studied soil-solution system (in absence of plants and roots). Adapted from Achat et al. (2009a). Total soil organic P includes P in living soil organisms (microbial P) and P in dead soil organic matter (Nziguheba and Bünemann, 2005). Decrease in the organic P pools during the incubation (–); increase in the inorganic P pools (+); fractions of sorbed ionic P that can diffuse as a function of time (↔). Net microbial P release = gross P remineralization – gross P immobilization = Δ microbial P pool size (decrease); Gross mineralization of P in dead soil organic matter = Δ pool size of P in dead soil organic matter (decrease) = Δ pool size of total organic P (decrease) = Δ pool size of total inorganic P (increase) when Δ microbial P pool size = 0 (evaluation at the end of the incubation experiment); Net mineralization of total organic P = net microbial P release + gross mineralization of P in dead soil organic matter; Flux from the microbial P pool to the pool of P in dead soil organic matter neglected.

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