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Effect of nutrients availability and long-term tillage on priming effect and soil C mineralization

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A B S T R A C T

Agricultural management practices including soil tillage exert strong control on soil organic matter (SOM) turnover and its interactions with global C cycle through different mechanisms. One control mechanism is the priming effect (PE) which consists in stimulating SOM mineralization with the addition of fresh, energetic plant material. In this study, we quantified C mineralization and PE in soils sampled in two contrasted long-term (40 years) tillage treatments which deeply modified soil properties (e.g. organic C concentration, microbial biomass, pH). We hypothesized that soil tillage might affect these processes through changes in C addition rates, nutrient availability, and long-term variations in SOM content and microbial communities. We investigated the relationship between PE intensity, tillage and nutrients availability in soil samples taken in no till (NT) and full inversion tillage (FIT) in two layers (0–5 and 15–20 cm). Soils were incubated with or without addition of ^{13}C labeled cellulose and mineral nutrients. Potential C mineralization and primed C were measured during 262 days. Unlabeled soil microbial biomass C was determined at the end of the experiment to separate apparent and real priming effect.

Basal cumulative C mineralization in the control soil ranged from 363 to 1490 mg kg^{-1} soil at day 262. It was strongly correlated with soil organic carbon (SOC) concentration. Specific mineralization rates were 44.8 and 68.8 g kg^{-1} SOC in the 0–5 cm layer for the FIT and NT treatments, respectively and were strongly linked with the particulate organic matter content ($r = 0.99^{***}$). These results suggest that SOC was more active in the upper layer of the NT treatment due to the high concentration of readily-decomposable, particulate organic matter. The cellulose was entirely metabolized after 60 days and its kinetics of mineralization was affected neither by tillage, depth nor nutrients. The percentage of cellulose C released as CO_2 represented 55–61% of the added cellulose-C at day 262. A positive PE was found in all treatments and its kinetics was parallel to that of cellulose mineralization. The cumulative PE significantly varied with nutrients level but not tillage, ranging from 73 to 78 mg kg^{-1} under high nutrients level and from 116 to 136 mg kg^{-1} in low nutrients level. No significant differences were found in unlabeled microbial biomass C between control and amended soil, suggesting no apparent priming effect. We conclude that the priming was mainly controlled by nutrient availability but not tillage, in spite of strong tillage-induced changes in SOC concentration and microbial biomass. Since PE is known to depend on C addition rate, tillage is expected to affect *in situ* PE through variations in the ratio of fresh carbon to nutrient concentration along the soil profile.

1. Introduction

Arable soils and their CO_2 emissions through SOM mineralization constitute a major source of uncertainties in predicting changes in atmospheric CO_2 concentration (Le Quéré et al., 2009; Eglin et al., 2010). Reducing this large uncertainty requires a better understanding and quantifying of biogeochemical process that

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control soil organic matter turnover (Houghton, 2003). Among the important process that influence SOM turnover, the so-called priming effect (PE) received a renewed interest (Kuzyakov et al., 2000; Zhang et al., 2013) and was shown to affect considerably the ecosystem C fluxes (Heimann and Reichstein, 2008). The PE was defined as "an extra decomposition of organic C after addition of easily-decomposable organic substances to the soil" (Dalenberg and Jager, 1989). In their meta-analysis, Zhang et al. (2013) showed that PE is more often positive than negative, indicating a stimulation of native C mineralization. Blagodatskaya and Kuzyakov (2008) distinguished between apparent priming where changes in microbial biomass turnover induce an extra release of CO_2 without effect on SOM decomposition and real priming when an additional mineralization of non-living SOM occurs. Sayer et al. (2011) showed that increasing litterfall in a lowland tropical forest enhanced carbon release from the soil. These findings were attributed to microbial PE which could be sustained over several years.

PE has been shown to depend on the nature of added substrate, the C addition rate, the mineral nutrient availability in soil and the characteristics of microbial community (Koranda et al., 2013; Thiessen et al., 2013). Various substrates have been evaluated: fructose, alanine, oxalic acid, catechol (Hamer and Marschner, 2005), wheat straw (Guenet et al., 2010) or cellulose (Fontaine et al., 2007, 2011) with variable PE responses: positive or negative reflecting interaction with other factors. The amount of added substrate effect on PE was examined in some studies. Guenet et al. (2010) tested the response of PE after addition of wheat straw to soil and found that PE increased asymptotically with the C addition rate. Paterson and Sim (2013) confirmed this tendency for glucose. The effect of nutrient concentration has been studied by Fontaine and Barot (2005) who proposed the concept of a "nutrient bank" mechanism that would regulate SOM mineralization and nutrients release through "microbial nitrogen mining". The microbial size and diversity may also influence PE. Bell et al. (2003) showed that PE is correlated to the size of the biomass and its composition, particularly the fungal: bacterial biomass ratio. Blagodatskaya and Kuzyakov (2008) found that PE is dependent on the ratio of added substrate to microbial biomass.

Soil tillage is a management practice which modifies most of these factors and is therefore susceptible to change PE intensity. We hypothesize that differential PE intensities might occur between soil layers and tillage treatments, and might help to explain the variations in SOM accumulation observed between different tillage systems (e.g. Dimassi et al., 2014). Very few studies have investigated the long-term effect of no-till (NT) versus full inversion tillage (FIT) systems on PE. Long-term NT leads to a marked stratification of organic carbon and probably nutrients such as mineral N and phosphorus (Thomas et al., 2007) compared to FIT which results in a much more uniform distribution within the soil profile. Changing tillage management can deeply modify chemical and microbiological properties able to generate variable PE intensity within the soil profile, particularly on the long-term.

The objective of this study is to determine tillage and nutrients availability impacts on PE intensity. We test the hypothesis that differences in SOC concentration, microbial biomass and nutrients availability induced by long-term contrasted tillage treatments may change PE intensity. We carried out a long incubation study (262 days) of soils sampled in a long-term experiment (40 years) comparing very contrasted tillage systems, in order to characterize SOC mineralization and PE intensity as affected by tillage management, soil depth and nutrients availability. In addition, we tried to extrapolate laboratory results to the field.

2. Materials and methods

2.1. Study site and soil sampling

The long-term experiment, established in 1970 and referred to as Experiment A1, is located at Boigneville in Northern France (48°19′38″N, 2°22′53″E) and set up at the experimental station of Arvalis-Institut du Végétal. The site has an average annual temperature and precipitation of 10.8 °C and 650 mm, respectively (Dimassi et al., 2013). The soil is classified as Haplic Luvisol, and its physical and chemical soil characteristics are shown in Table 1. Before the beginning of the experiment, the field was managed under annual crops with full inversion tillage to about 28 cm depth for many years. Since 1970, the field had been under two contrasting tillage treatments for more than 40 years: continuous NT without soil disturbance except for sowing and continuous FIT where soil is mouldboard plowed every year down to about 25 cm depth and undergoes other tillage operations: disk plowing after harvest at two dates and seedbed preparation at sowing. A two year rotation of maize/winter wheat was implemented in all plots. In the studied plots, crop residues were always returned either mixed with soil by tillage in FIT or left at soil surface in the NT treatment. On 14 June 2010, we collected two sets of soil cores on each side of the rectangular plot and in each of the two blocks, which provided four true replicates. Soil samples were taken in the maize inter-row with a cylindrical auger of 6 cm diameter. Two soil layers (0–5 and 15–20 cm) were isolated from soil cores. Residues present at soil surface were removed before sampling and soil samples were stored at 4 °C before subsequent analyses and incubation.

2.2. Incubation experiment

Fresh soil samples were first sieved at 2 mm and visible residues remaining were removed by hand picking. The soil was then centrifuged at 3500 rpm to obtain a water potential of about −100 kPa and pre-incubated for two weeks at 20 °C. The experimental design included 48 samples divided into 12 treatments with 4 true replicates (Table 2). Half of the soil samples were amended with cellulose at a rate of 882 mg C kg^{-1} dry soil (S1–S6) and the other half consisted in control samples (C1–C6). The six treatments included two soil layers (0–5 cm and 15–20 cm)

Table 1
Physical and chemical soil properties (measured in June 2010).

			FIT[c]		NT[c]	
			0–5 cm	15–20 cm	0–5 cm	15–20 cm
Whole soil						
Clay	<2 μm	g kg^{-1}	235	233	241	262
Fine silt	2–20 μm	g kg^{-1}	301	302	313	300
Coarse loam	20–50 μm	g kg^{-1}	365	372	364	352
Fine sand	50–200 μm	g kg^{-1}	77	72	64	67
Coarse sand	200–2000 μm	g kg^{-1}	22	21	18	19
CEC[a]		C mol kg^{-1}	12.1	11.7	12.7	12.7
pH			6.5	6.6	5.3	7.0
Organic C		g kg^{-1}	11.8	9.7	18.4	9.8
Total N		g kg^{-1}	1.43	1.18	1.94	1.18
Particulate organic matter[b]						
POM-C		mg kg^{-1}	475	220	2114	71
POM-N		mg kg^{-1}	24.3	12.1	105.2	3.7

[a] Cation-exchange capacity (Metson method).
[b] Free POM (>200 μm).
[c] FIT = Full inversion tillage; NT = No-Till.