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Effect of low temperature and soil type on the decomposition rate of soil organic carbon and clover leaves, and related priming effect

R.B. Frøseth [a, b, *], M.A. Bleken [b, 1]

[a] Bioforsk – Norwegian Institute for Agricultural and Environmental Research, Organic Food and Farming Division, Gunnars Veg 6, N-6630 Tingvoll, Norway
[b] Norwegian University of Life Sciences, Department of Environmental Sciences, Fougnerbakken 3, N-1432 Ås, Norway

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ABSTRACT

The purpose of this study was to improve the temperature response function to be used in models of soil organic carbon (SOC) and litter mineralisation. A clay soil and a sandy soil with equivalent weather and cultivation history were incubated for 142 days at 0, 4, 8.5 or 15 °C, which is representative for the natural temperature range above 0 °C of these soils. The soils were incubated with or without ^{13}C labelled clover leaves in gas tight chambers. In absence of added plant litter, the decomposition rate [mol CO_2 (mol substrate-C)$^{-1}$ day^{-1}] of SOC followed a first order reaction and it was twice as fast in the sandy soil as in the clay soil. Contrary to our hypothesis, the relative response of SOC mineralisation rate to temperature was the same in both soils; it was well described by an Arrhenius function and it could also be approximated as a linear function of temperature. The mineralisation of clover leaves was affected by soil type, and was slower in the clay than in the sandy soil. Also the initial temperature sensitivity of the clover decomposition (to 18% decomposed) could be approximated by a linear function. SOC mineralisation was enhanced (priming effect) by the presence of clover; the relative increase was most conspicuous at 0 °C (150–250% over 142 days, depending on the soil) and decreased with temperature (+40% at 15 °C). At the start of the incubation and up to 52 days of incubation the priming effect was correlated with the amount of CO_2 derived from mineralisation of clover leaves. We suggest that the effect of soil type on the diffusivity of enzymes could be an important mechanism affecting the decomposition rate and probably also the volume of soil exposed to priming around decomposing litter.

In conclusion, the temperature sensitivity of the decomposition was in the order: priming < plant litter < sandy soil SOC = clay soil SOC. For the purpose of modelling, we present parameterised equations for mineralisation rates of SOC and clover leaves as function of soil temperature range 0–15 °C. Regarding modelling of priming, there is scope for relating it to litter decomposition and the influence of soil type on the diffusion of enzymes from microorganisms around the litter surface. The effect of soil type on plant litter decomposition and soil priming should be considered in models that predict nitrogen mineralisation based on the C/N stoichiometry of substrates and decomposition products.

1. Introduction

In farming systems, plant residues are incorporated into the soil for the purpose of preparing a new seedbed. In addition, some crops, e.g. green manure and catch crops, are grown and incorporated into the soil for the purpose of increasing soil fertility and thereby enhance the yield of subsequent crops. In cold temperate regions, the incorporation is often done in the autumn or spring, and the decomposing organic matter in the soil is exposed to low temperatures before a new crop is established or when nutrient uptake by plants is still small. Several studies have shown substantial carbon (C) and nitrogen mineralisation of incorporated green manure at temperatures down to 1–3 °C (Breland, 1994; Van Schöll et al., 1997; Cookson et al., 2002). Thus, the incorporation of crops grown for enhanced C-sequestration can increase the risk of nitrogen losses as gaseous emissions, surface runoff and leaching of nitrate or soluble organic nitrogen. As the input of fresh plant material from leys, and in particular from green manure crops can be considerable, an improved modelling of C mineralisation during

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[*] Corresponding author. Bioforsk – Norwegian Institute for Agricultural and Environmental Research, Organic Food and Farming Division, Gunnars Veg 6, N-6630 Tingvoll, Norway. Tel.: +47 40481328; fax: +47 71534405.
E-mail addresses: randi.froseth@bioforsk.no (R.B. Frøseth), marina.bleken@nmbu.no (M.A. Bleken).
[1] Tel.: +47 67231831.

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the cold season is a valuable tool for predicting nitrogen mineralisation, and thus for planning a better crop management with higher nitrogen use efficiency and reduced environmental risk.

Most models of soil organic matter (SOM) decomposition assume that SOM can be divided into a number of more and less decomposable pools and that their decomposition is proportional to the amount of substrate, i.e. that it follows first order kinetics (Manzoni and Porporato, 2009). Thus the amount C of an initial pool C_0 remaining after time t can be expressed as.

$$C = C_0 e^{-kt} \tag{1}$$

where k is the decay rate constant. One of the most commonly used functions for describing the dependency of decomposition on temperature is the Arrhenius equation (Davidson and Janssens, 2006):

$$k = A e^{-E_a/(RT)} \tag{2}$$

where A is the pre-exponential factor, E_a is the required activation energy, R is the universal gas constant and T is the temperature in Kelvin. For the purpose of modelling, the temperature sensitivity can be expressed as a temperature function $f(T)$ that modifies a decay rate k_{ref} at a reference temperature (Kutsch et al., 2009; Moyano et al., 2009; Davidson et al., 2012):

$$k = k_{ref} f\left(T\right) \tag{3}$$

Thus, the sensitivity to temperature can be seen as the change in decay rate relative to the decay rate at another temperature (Reichstein and Janssens, 2009). The most commonly used temperature factor is the Q_{10} which expresses the relative change in k when temperature increases by 10 °C (Kirschbaum, 2006):

$$Q_{10} = (k_2/k_1)^{10/(T_2-T_1)} \tag{4}$$

where k_2 and k_1 are respiration rates observed at temperatures T_2 and T_1. In their review of 25 incubation studies of soil, straw and soil with different substrates, Kätterer et al. (1998) found Q_{10} of 2 to be adequate for organic matter decomposition in the temperature range 5–35 °C. However, Q_{10} decreases with increasing temperature, a fact which is also predicted by the Arrhenius equation (e.g. Davidson and Janssens, 2006), and for the lower temperature range (<10 °C) Q_{10} is found to be greater and almost 8 at 0 °C (Kirschbaum, 1995; Leifeld and Fuhrer, 2005; Farrar et al., 2012). This complicates the use of Q_{10} as factor for modelling the decomposition of organic matter (Reichstein and Janssens, 2009).

How readily the organic matter in the soil is decomposed depends on its chemical quality and different abiotic constraints, which are likely to affect the response to temperature (Davidson and Janssens, 2006). Kinetic theory predicts that the temperature sensitivity of SOM decomposition should increase as the degree of substrate complexity increases (Bosatta and Ågren, 1999). Therefore the decomposition of older SOM, consisting of more complex, recalcitrant organic molecules, should be affected more by temperature than new SOM. However, results regarding the temperature sensitivity of different organic matter fractions are contradictory (Kirschbaum, 1995; Kätterer et al., 1998; Liski et al., 1999; Giardina and Ryan, 2000; Fang et al., 2005; Fierer et al., 2005; Lefèvre el al., 2014). In modelling, the same modifying temperature function $f(T)$ is often applied to all substrates in a soil, mainly as a precautious conservative rule since there is a lack of sufficient empirical evidences that can be transposed to field conditions (Coleman and Jenkinson, 1999; Hansen, 2002; Jansson and Karlberg, 2004).

Soil type is among the abiotic factors that influences decomposition. The binding of organic matter to mineral surfaces and occlusion in soil aggregates acts as chemical and physical protection of organic substrates and microbial biomass (Van Veen et al., 1985; Gregorich et al., 1991; Saggar et al., 1996; Müller and Höper, 2004; Davidson and Janssens, 2006). The adsorption of soil organic carbon (SOC) to mineral particles is expected to increase the effect of temperature on k, since higher activation energy is needed to break the bonds between the organic matter and the mineral particles (Conant et al., 2011).

The decomposition of SOM can be influenced by the addition of readily decomposable plant residues and root exudates (e.g. Löhnis (1926) referred by Kuzyakov et al., 2000; De Graaff et al., 2010; Lukas et al., 2013). Kuzyakov et al. (2000) has defined the priming effect (PE) as short term increased or decreased turnover of SOM caused by any soil treatment. Reports of direct effects of temperature on priming are also rare and cannot be generalized (Kuzyakov, 2010). Recently, PE was observed at 4 °C (Farrar et al., 2012) and around freezing point (Lukas et al., 2013). Farrar et al. (2012) and Ghee et al. (2013) found that priming caused by the addition of easily degradable substrates (glucose/amino-acids) was not altered by temperature. Thiessen et al. (2013) studied the decomposition during 199 days of fresh plant material in soil at two diurnal temperature treatments (5–15 °C, 15–25 °C) and found that the PE relative to the mineralisation of the non-amended soil was similar at the two temperature treatments.

The aim of our study was to estimate the effect low temperature and soil type have on the decomposition of SOC and of newly incorporated clover leaves. We used two soils, a sandy and a clay soil, with similar cultivation history and environmental conditions to avoid confounding of soil type with these factors. The temperature range was that normally experienced in the plough layer of Norwegian soils, when they are not frozen, with temperature intervals between treatments unevenly distributed (i.e. 0, 4, 8.5, 15 °C), in order increase the power of the statistical estimates at the lower temperatures (Kirschbaum, 2006).

The following hypothesis were tested: i) The sensitivity to temperature of decomposition is inversely proportional to the decomposition rate, and in the order plant litter << sandy soil SOC < clay soil SOC, ii) Neither chemical binding, nor adsorption or occlusion affect the decomposition of newly incorporated plant residues, therefore soil type does not affect the initial decomposition rate of plant litter, and iii) During decomposition of plant litter, a positive PE (including microbial biomass turnover) occurs, and its response to temperature is more similar to that of litter rather than to that of SOC mineralisation. The last hypothesis is based on the consideration that PE is likely to be the result of increased exo-enzymes production from microbial activity stimulated by easily decomposable plant residues.

2. Materials and methods

2.1. Experimental design

The incubation experiment ran for 142 days with two soil types in gas tight glass chambers, with or without ^{13}C labelled clover leaves, at 0, 4, 8.5 or 15 °C. The soils were taken from two arable irregular cereal-leys rotation fields, about 4 km apart, of the Bioforsk research center Kvithamar in Central Norway (63°29′N, 10°52′E). In this humid costal climate the normal value (1961–1990) for annual precipitation is 896 mm and the mean monthly soil temperature at 10 cm depth is between −1 and 15 °C (Appendix A).

The soils were a silty clay loam (clay soil) classified as Mollic Gleysol and a sandy loam (sandy soil) classified as Arenic Fluvisol