Soil Restoration Practices Effects on Priming Effect Intensity and Carbon Fluxes

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Abstract

Background

The decomposition of soil organic matter (SOM) is one of the most important processes influencing the global carbon (C) cycle, the physico-chemical characteristics of soils, the mineralization of nutrients for plant growth and soil food webs. Yet, priming effects are considered to be large enough to influence ecosystem carbon fluxes. Here we have tested the effects of soil restoration practices on priming effect and carbon fluxes.

Result

Our results suggest that indirect effects are such as altered stabilization of older C associated with the increased inputs of fresh plant inputs ('priming') add uncertainty to the prediction of future soil C responses. Far ahead restoration influence the amount and composition of the decomposer organisms, including soil fauna, as well as the soil microbial community, by inducing up to more CO_2 emission with fresh millet straw addition in fresh state than pre-decomposed one. Restoration had a very strong impact (increase by 22.7%) on basal soil organic matter mineralization but not on priming effect. The PE of non-restored site was lower than that of restored site by 14.9–22.7%; the lowest mineralization per unit carbon was recorded in the non-restored. Through the "4 per 1000" initiative, it has been very recently demonstrated that priming effect could have a noticeable impact on soil carbon sequestration.

Conclusion

We have shown in our study that the degraded soil played a dominant positive role in the soil organic carbon mineralization. Our results provide solid evidence that SOC content plays a critical role in regulating apparent priming effects, with important implications for the improvement of C cycling models under global change scenarios.

Highlights

(1) The added organic compounds to SOM is an important factor in PEs.

(2) Priming effect (PE) is more influenced by trigger mulch concentrations.

(3) Triggering of PEs in soils by litter is not only influenced by litter quality but also by the ability of the predecomposed litter.

Introduction

The knowledge about soil carbon sequestration is extremely important to determine restoration practices which keep carbon in the terrestrial environment and appropriate forms of soil conservation in Sahelian ecosystems. Soil carbon depends on vegetation cover. Any change in land use may significantly alter related source or sink characteristics for atmospheric CO_2 and other GHGs (Sainju et al. 2008; Poeplau and Don 2013). Changes in tropical natural ecosystems may cause reductions in carbon inputs depending of the use, management, physical, chemical and biological soil (Cardoso et al. 2013).

Soil organic carbon (SOC) stocks amount to an estimated 1,500 ±230 GtC in the first meter of soil, but until now soils have been a global net source of GHGs. These losses are strongly affected by land use, land use change, vegetation cover and soil restoration. SOC stocks in the upper soil layers (first 40 cm) are especially sensitive and responsive to such changes in land use and management, which provides an opportunity to influence the amount of CO_2 in the atmosphere. This can be achieved by maintaining existing soil carbon stocks (of particular importance in soils with high SOC content), or by soil carbon sequestration. Soil restoration 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. 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 (Bastida et al. 2019; Paolo Di Lonardo et al. 2019).

Mulching is a restoration practice which modifies most of these factors and is therefore susceptible to change PE intensity. The quality of added substrates, defined by chemical structure complexity and stoichiometry, can have different effects on PE (Bastida et al. 2019). It has been suggested that a high degree of physicochemical similarity between added compounds and SOM fractions will result in a positive priming effect.

Even though the addition of FOM does not always result in a PE, the most frequently reported response is the acceleration of SOM mineralization, sometimes with a rate up to 400% (Sun et al. 2019). The priming effect is likely a universal phenomenon that could affect significantly the C accumulation ability of soils in very different contexts. The CO_2 fertilization effect (*i.e.* the increase in photosynthesis due to the increase in atmospheric CO_2 concentration), for example, could lead to a weaker gain of soil C than expected or even to a net loss of soil organic C (SOC) stocks

As the restoration practices designed to increase SOC stocks are generally based on an increase of C inputs to the soil, the PE may reduce the impact of such practices and make the yearly SOC stock increase targeted by the 4 per 1000 difficult to achieve (Rumpel and Chabbi 2021). Since mulch provides the primary source of SOM formation, it is likely that SOM-degrading microbes are, to some extent, specialized on their substrate. According to the latter theory, addition of substrates with high C/N ratio will stimulate positive PEs.

Positive priming occurs when new C inputs lead to an increase in the mineralization of existing, older SOC, and is thus considered here as a destabilizing force. In nature, inputs that lead to priming can occur via the addition of fresh plant litter, the delivery of leached dissolved organic matter through soil pores, or root exudates and rhizodeposits, whose priming effects are known specifically as rhizosphere priming.

Positive priming effects can be significant and have been suggested as the mechanisms behind a lack of increased soil C after long-term CO_2 fertilization (Sun et al. 2019). The amount of carbon added can affect the magnitude and direction of the priming effect (Hicks et al. 2019), which may explain the lack of positive priming at C-poor sites.

Here, we evaluated the effects of soil restoration on PE and associated drivers for such effects. Then, we will address the following hypotheses: positive PE will also increase with increasing availability of the added mulch that resemble fractions of recalcitrant SOM, there is a positive relationship between litter decomposition and priming.

Materials And Methods

Plant material & pre-decomposition.

We used fresh millet mulch. The half of this FOM was pre-decomposed manually. The mulch was first dried at 30 °C for 10 days, and then finely milled. The milled plant material was distributed in 12 litterbags (mesh size 35 µm), which was then placed on top of 600 g of soil A (dry weight equivalent) at 80% of the water holding capacity (WHC), itself in 4 polyethylene containers. The containers were covered with Parafilm to minimize evaporation without affecting other gas exchanges (Abdallah et al. 2021) (and thus prevent CO_2 accumulation) and placed in incubation chambers at 25°C for 3 months. The location of the containers in the incubation chambers was randomized weekly.

The litterbags were weighed before and at the end of the incubation in order to determine mass loss. At the end of this pre-decomposition step, the pre-decomposed millet straw (thereafter called DeOM).

Experimental design.

The present study was conducted during the dry season with the following treatments using millet as the test crop: The experimental design was fully factorial with four factors, three of which had two levels and one of which had three levels.

There were two levels of nutrient addition (with or without) and 3 types of OM addition (fresh (FOM) or pre-decomposed (DeOM) millet straw and a control treatment (CTL) without straw).

Data analyses

Raw material was calculated as the cumulative mineralized CO2-C. The results per gram of soil (gsoil) were normalized per gram of soil carbon (gCsoil) and cumulated over the 101 days of incubation. The differences in cumulative CO_2 respiration (including total CO_2, SOM-derived CO_2 and added OM-derived CO_2) and PE (including relative PE and cumulative PE) were analyzed using two-way ANOVA. Significant differences between the various treatments were tested with the Tukey HSD test. Statistical analysis was performed using R version 3.4.1 (R Core Team 2019).

Results

Total mineralization

Tukey's test showed that C mineralization was almost the same for the decomposed organic matter and the fresh organic matter. The input of organic matter always induced a higher mineralization compared to control (+51% on average) for both pre-decomposed and fresh modalities, but only +18% with decomposed organic matter versus +85% with the fresh organic matter. The patterns were similar in the restored plots, though the differences were more marked in the degraded soil.

Added OM derived-CO2

Addition of FOM and DeOM to soil induced a cumulative positive CO_2 (2.79 to 3.24 mgC g^{-1}) from SOM decomposition over 200 days. The mineralization of added organic matter was 2 times higher than that of the non-restored ones (Figure 2). Indeed, post-hoc tests suggest that added OM mineralization was quite sensitive to the incubation period.

SOM derived-CO_2 – priming effect

N input modifies the priming effect (PE), that is, the effect of fresh organics on the microbial decomposition of SOM. The PE depended mainly on both the quality of OM addition (Figure 3). The maximum PE was induced by the addition of easily mineralizable compounds (FOM), which induced up to +3% higher mineralization of DeOM compared to the control. The PE profile over time depended on the status of OM addition. There was little or no PE following the addition of DeOM, regardless of the soil. In soil A, the PE after the addition of FOM was relatively high and persisted throughout the duration of the incubation, whilst it was lower and reached a plateau after 100 days in soil F (Fig 2).

Interactions between treatments

A positive relationship between litter and priming HFA was found, indicating that the rates of both litter decomposition and PE may be affected in the same manner by the environmental conditions and litter versus away the soil.

Discussion

The addition of organic substrates to soil accelerated soil organic matter (SOM) mineralization (positive priming effect), indicating the importance of energy obtained from trigger-substrates for PEs. With our hypothesis about the PE theory, the quality of the organic material brought has strongly impacted the mineralization of the different types of organic matter. First, once incorporated into the soil, the mulch itself was mineralized 3 to 8 times more when it was fresh rather than pre-decomposed, which reflects a higher availability to microbial decomposers of the energy it contained, *i.e.* a better degradability (Raczka et al. 2021). In other words, this confirms that the pre-decomposition stage decreased the lability: recalcitrance ratio of the original plant material compounds (Zhang and Zhou 2018). Obviously, this large difference in degradability affects total mineralization, but in addition to this, it also affected the mineralization of SOM, *i.e.* it affected PE. Indeed, by providing energy more easily accessible to soil microorganisms, fresh straw induced a higher mineralization of the SOM compared to that induced by pre-decomposed straw and control without input, particularly on the agricultural soil (Wang et al. 2015). The first hypothesis of this study namely that the addition of fresh millet straw would stimulate PE to a greater extent than the addition of pre-decomposed millet straw was validated. This underpins that an avenue for increasing soil C stocks in cultivated soils might be to add decomposed straw residues rather than incorporating them fresh. It should be noted that the PE was much lower in the degraded soil, suggesting that microbial communities were less C limited in this soil (Cely et al. 2014). This suggests that the energy perspective alone cannot explain the differences in PEs observed. This result further tends to confirm the idea that our pre-decomposing phase made mulch residues more biochemically recalcitrant (Tiefenbacher et al. 2021). Indeed, the temperature sensitivity of mineralization was quite similar for the DeOM and for the SOM, while for the FOM it was lower. Agricultural and degraded soils differ by several aspects such as OM type, dynamics of OM inputs and outputs, exposition to climatic and anthropic disturbances (Guo & Gifford 2002). This led to three main differences noticed here between soil responses. Despite all the differences noticed between results obtained on these two agrosystems, general mineralization patterns were similar for the two types of ecosystem and underpin a certain robustness of our results. Particularly, our main hypothesis was validated on both soils: the quality of the organic matter brought in the form of fresh or pre-decomposed straw residues led to very significant differences in the intensity of the induced PE. This further supports that the quality of added OM inducing the PE process is a major factor to take into account for SOC dynamics. In other words, this means that, depending of the land-use (such as degradation for farmland establishment) and agricultural practices (as input of highly degradable FOM), soils can become a significant source of CO_2 by the mineralization of large amount of stable C (Wang et al. 2020). Yet it also means that with better understandings and practices, this agricultural soil has the potential to store at least –2.19 times more C (Minasny et al. 2017), as its degraded counterpart and neighbor. To summarize, in the conditions of the present study, we were able to test the impacts of several factors and their combinations on the mineralization of different pools of organic matter and PE. The land cover appeared to have strong interactions with all other factors, but surprisingly, no relevant interactions were noticed between the other factors, and this for all the mineralization of all OM pools. Quality of OM and nutrients availability did not induce notable feedbacks on global changes through their interactions under laboratory conditions. However, the addition of fresh OM induced a large PE whereas the addition of pre-decomposed OM led to no significant effect, *i.e.* the quality of OM was the most determinant factor far ahead the temperature and nutrients availability. Consistent with the concept of PE, this suggests that the quality of the OM provided is a key element to consider with regard to the storage-loss dynamics of SOC, and so, of SOM (Wang et al. 2015). Furthermore, as suggested by the stable efficiency of the process within each soil, PE seemed to be very dependent on the bio-available C. While the increase in temperature strongly impacted the basal mineralization of the soils which confirms the worrisome positive feedback on global warming, no significant effect was detected on PE itself.

Conclusion

In our study, the effect of soil restoration through mulching appeared to induce the greatest impact on the PE, to the point of rendering the expected responses to the carbon storage. The level of easily available energy contained in amendments (*i.e.* OM quality) have to be highly monitored for the soil fertility and productivity, in order to prevent C losses and optimize soil ecosystem services, as long term C storage and climate change. Further studies are needed to assess the importance of the factors tested here under more realistic conditions up to *in situ* field experiment, and also to test the response of PE with plant residues from other crop species and other pre-decomposition and composting methods, in order to assess the potential of this approach. These results show the importance of paying particular attention to these issues in our critical context of global change and lack of sustainability for agricultural practices.

Declarations

Ethics approval and consent to participate

Author confirmed that there is no ethical conflict.

Consent for publication

Author has read the manuscript carefully and agreed to submit it for publication.

Availability of data and materials

All the data included in this manuscript will be provided once the paper will be published.

Competing interests

Author declares that there are no competing interests.

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Authors' contributions

A. Amadou Issoufou, H. Y. Bachirou: Conceived and designed the analysis; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

I. Soumana, G. Maman, M. Sabiou: Performed the experiments; Analyzed and interpreted the data, materials, analysis tools or data, wrote the paper.

A. Mahamane: Conceived and designed the experiments, wrote the paper.

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Figures

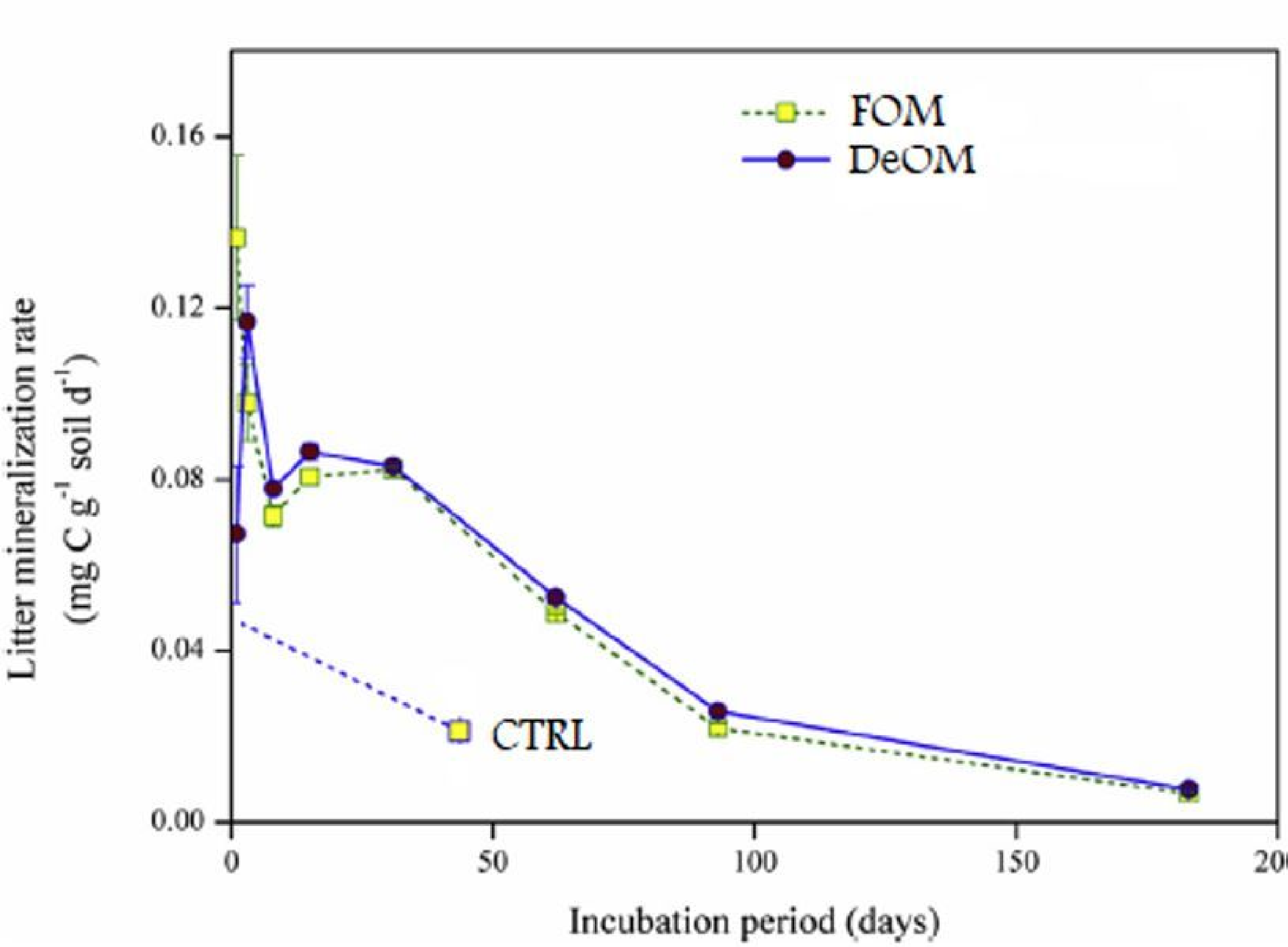

Figure 1

The patterns of carbon mineralization for different organic materials

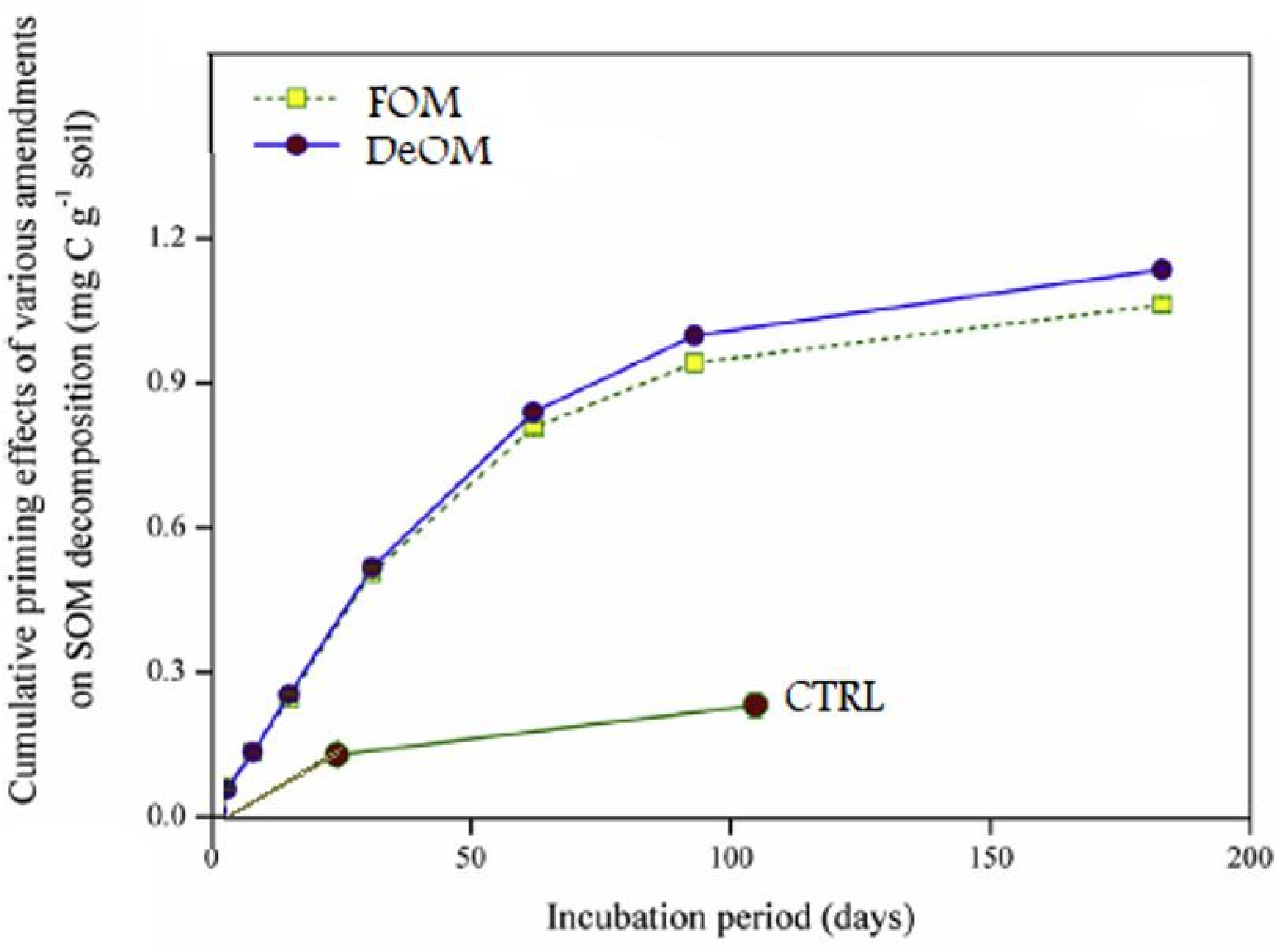

Figure 2

Cumulative CO2 derived from soil organic matter (SOM) and the cumulative priming effects of different amendments on SOM decomposition with incubation time

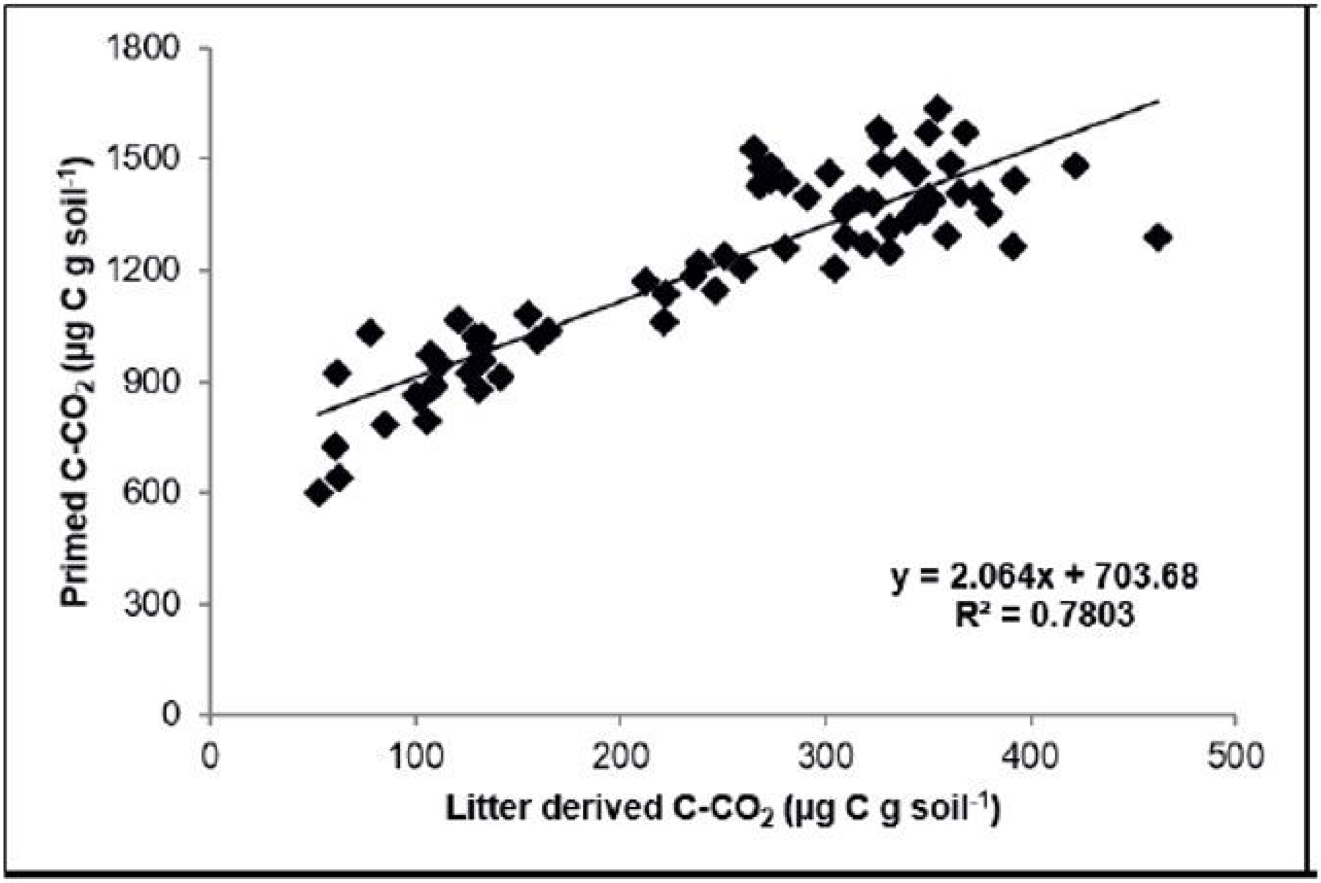

Figure 3

correlation between litter-derived CO2 and PE