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Research Article

Soil Restoration Practices on Priming Effect Intensity and Carbon Fluxes

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The decomposition of soil organic matter (SOM) is one of the most important processes influencing the global carbon (C) cycle, the physicochemical characteristics of soils, and 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 effects and carbon fluxes. Our results suggest that indirect effects 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. In addition, restoration influences the abundance and diversity of decomposers, as well as the soil microbial community, by inducing up to more CO_2 emission with fresh millet straw addition in fresh state than the predecomposed one. Restoration had strongly increased the impact by up to 22.7%, while the priming effect (PE) mineralization did not increase. The latter of the nonrestored site was lower than that of the restored site by 14.9–22.7%; the lowest mineralization per unit carbon was recorded in the nonrestored site. Through the "4 per 1000" initiative, it has been very recently demonstrated that priming effects could have a noticeable impact on soil carbon sequestration. The study has revealed 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.

1. Introduction

The knowledge about soil carbon sequestration is extremely important to determine which of the restoration practices provide opportunities for soil carbon stabilization 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 carbon dioxide CO_2 and other GHGs [1, 2]. Changes in tropical natural ecosystems are likely to cause reductions in carbon inputs depending on the use, management, physical, chemical, and biological soil [3].

Soil organic carbon (SOC) stocks amount to an estimated $1{,}500 \pm 230$ 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 exerts a 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 materials. The PE has been shown to depend on the nature of the added substrate, the C addition rate, the mineral nutrient availability in soil, and the characteristics of microbial community [4, 5].

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 the PE [4]. 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 fresh organic matter (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% [6]. The priming effect is likely a universal phenomenon that could significantly affect 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 are generally designed to increase SOC stocks based on the increase of C inputs to the soil, the PE may reduce the impact of such practices. Hence, the increase of yearly SOC stock targeted by the 4 per 1000 initiative will be difficult to achieve [7]. 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 [6]. The amount of carbon added can affect the magnitude and direction of the priming effect [8], which may explain the lack of positive priming at C-poor sites.

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

2. Materials and Methods

2.1. Plant Material and Predecomposition. We used fresh millet mulch. The half of this FOM was predecomposed 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 [8] (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 predecomposition step, the predecomposed millet straw was weighted.

2.2. 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 predecomposed (DeOM) millet straw and a control treatment (CTL) without straw).

2.3. Data Analyses. The raw material was calculated as the cumulative mineralized CO_2-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.

3. Results

3.1. Total Mineralization. Tukey's test showed that C mineralization was almost the same for the decomposed organic matter and the fresh organic matter (Figure 1). The input of organic matter always induced a higher mineralization compared to control (+51% on average) for both predecomposed 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.

3.2. Added OM Derived-CO_2. FOM and DeOM were added to the soil to induce 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 two times higher than that of the nonrestored ones (Figure 2). Indeed, post hoc tests suggest that added OM mineralization was quite sensitive to the incubation period.

3.3. SOM Derived-CO_2-Priming Effect. Nitrogen 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

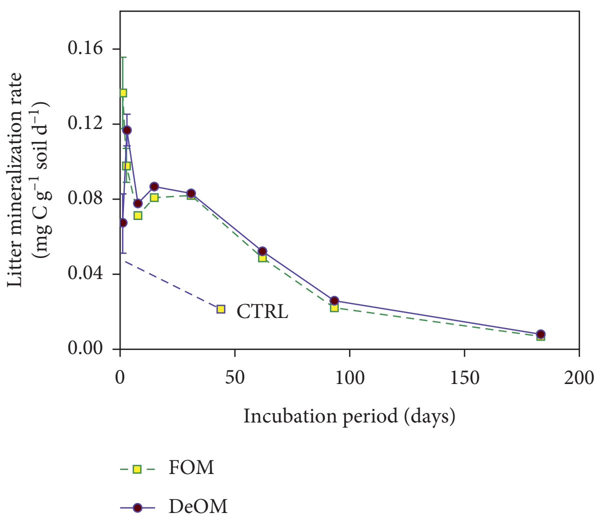

Figure 1: The patterns of carbon mineralization for different organic materials.

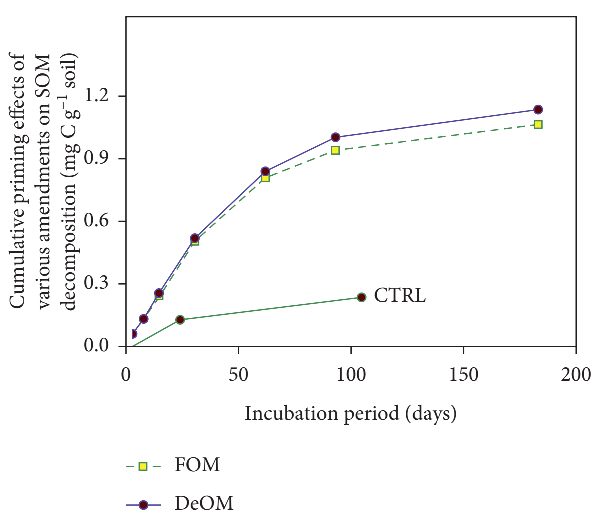

Figure 2: Cumulative CO_2 derived from soil organic matter (SOM) and the cumulative priming effects of different amendments on SOM decomposition with incubation time.

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 (Figure 3).

3.4. Interaction between Treatments. A positive relationship between litter and priming HFA was found, indicating that the rates of both litter decomposition, and the PE may be affected in the same manner by the environmental conditions and litter versus away the soil (Figure 4).

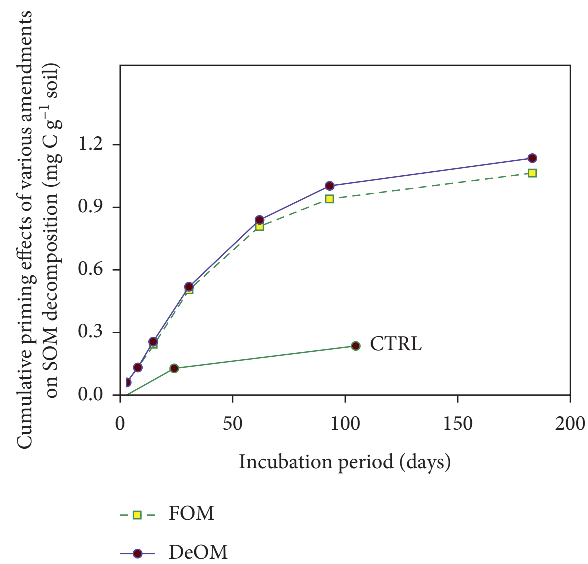

Figure 3: Priming effects of various amendments on SOM decomposition with time incubation.

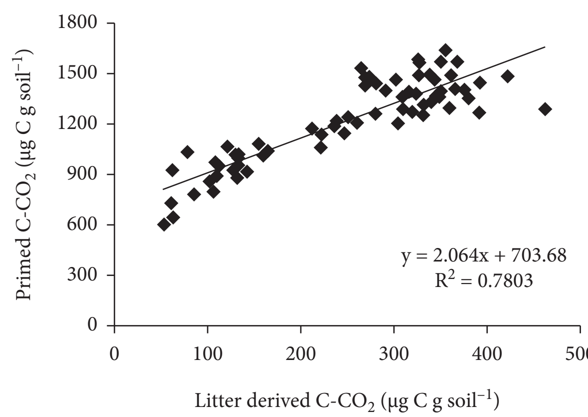

Figure 4: Correlation between litter-derived CO_2 and PE.

4. 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 bought has strongly impacted the mineralization of the different types of organic matter. First, once incorporated into the soil, the mulch itself was mineralized three to four times more when it was fresh rather than predecomposed, which reflects a higher availability to microbial decomposers of the energy it contained, i.e., a better degradability [9, 10]. In other words, this confirms that the predecomposition stage decreased the lability: recalcitrance ratio of the original plant material compounds [11]. 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 the 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 predecomposed straw and control without input, particularly on the agricultural soil [12]. The first hypothesis of this study, namely, that the addition of fresh millet straw would stimulate the PE to a greater extent than the addition of predecomposed 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 [13]. This suggests that the energy perspective alone cannot explain the differences in PEs observed. This result further tends to confirm the idea that our predecomposing phase made mulch residues more biochemically recalcitrant [14]. 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 the OM type, dynamics of OM inputs and outputs, and exposition to climatic and anthropic disturbances [13]. This led to three main differences being noticed here between soil responses. Despite all the differences noticed between the results obtained on these two agrosystems, general mineralization patterns were similar for the two types of ecosystems and underpin a certain robustness of our results. Particularly, our main hypothesis was validated on both soils: the quality of the organic matter bought in the form of fresh or predecomposed 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 on 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 [15], 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 PEs. 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 was for all the mineralization of all OM pools. The quality of OM and nutrient 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 predecomposed OM led to no significant effect, i.e., the quality of OM was the most determinant factor far ahead the temperature and nutrient availability. Consistent with the concept of the 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 [12]. Furthermore, as suggested by the stable efficiency of the process within each soil, the PE seemed to be very dependent on the bioavailable 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 the PE itself.

5. Conclusion

The addition of readily decomposable C to the soil, in the present case, through organic materials' application, stimulates the soil biomass activity and consequently, the decomposition of native SOM.

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 available energy contained in amendments (i.e., OM quality) has 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. However, the N mining theory has been challenged as the simultaneous addition of C and N was shown to simulate rather than decrease priming.

The physicochemical properties of PE-trigger substrates have been indicated to be important for the direction and magnitude of PEs. Further studies are needed to assess the importance of the factors tested here under more realistic conditions up to *in situ* field experiments and also to test the response of PE with plant residues from other crop species and other predecomposition and composting methods, in order to assess the potential of this approach. These results showed the importance of paying particular attention to these issues in our critical context of global change and lack of sustainability for agricultural practices.

Data Availability

The data used to support the findings of this study are available in the database of the University of Diffa (https://univ-diffa.ne/publications-scientifques).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

A. Amadou Issoufou and H. Y. Bachirou conceived and designed the analysis; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, and analysis tools or data; and wrote the paper. I. Soumana performed the experiments; analyzed and interpreted the data, materials, analysis tools or data; and wrote the paper. A. Mahamane conceived and designed the experiments and wrote the paper. The authors have read the manuscript carefully and agreed to submit it for publication.

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