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LETTER TO THE EDITOR

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On the importance of time in carbon sequestration in soils and climate change mitigation

A clear definition of carbon (C) sequestration in soils is necessary to accurately quantify the role of soil in climate change mitigation. Don et al. (2023) proposed defining carbon sequestration as "[the] Process of transferring carbon from the atmosphere into the soil through plants or other organisms, which is retained as soil organic carbon (SOC) resulting in a global C stock increase of the soil". This definition is based on the definitions provided by IPCC (2001) and Olson et al. (2014). We agree with Don et al. (2023) that this term is often used misleadingly, which may lead to erroneous or biased quantifications of the role of soil in climate change mitigation. However, in our view, the definition proposed by Don et al. (2023) is incomplete and misses important previous discussions on the topics of permanence and the time carbon spends stored in soil. A comprehensive definition of carbon sequestration should explicitly include the time that carbon remains stored in an ecosystem and remains removed from the atmosphere, thus mitigating its contribution to the greenhouse effect.

Carbon fixed during photosynthesis returns to the atmosphere over a wide range of temporal scales involving phenomena with fast dynamics, such as respiration of simple photosynthates, and slow dynamics, such as organic matter transfers to soil and subsequent slow decomposition (Muñoz et al., 2023; Sierra et al., 2021; Trumbore, 2009). The multiple timescales of the processes and variables driving the carbon cycle can lead to significantly different effects of carbon sequestration on global warming mitigation, depending on when these effects are assessed.

A complete quantification of the role of terrestrial ecosystems in carbon retention from the atmosphere should involve both how much and for how long carbon is sequestered. However, little attention has been paid to the fate of carbon once it enters the ecosystem and the time it spends there, compared to the attention given to quantifying carbon, stocks, sources, and sinks. Furthermore, rates at which C enters the soil can influence the efficiency of different measures of SOC sequestration (Olson et al., 2014). For instance, increases in the amount of carbon stored under management measures such as planting more productive crops, higher allocation to root systems or adding exogenous amendments do not necessarily increase the time the carbon will remain out of the atmosphere. Thus, a consolidated definition of carbon sequestration that does not consider directly that time will reinforce an incomplete view of the role of terrestrial ecosystems in climate change mitigation.

Previous authors have defined carbon sequestration by explicitly considering the time that carbon atoms remain in the ecosystem (e.g. Sedjo & Sohngen, 2012; Sierra et al., 2021), and even Olson et al. (2014) considered time in their definition of carbon sequestration. The complete definition provided by Olson et al. (2014) has a second part that Don et al. (2023) did not include in their definition, which is "Retention time of sequestered carbon in the soil (terrestrial pool) can range from short-term (not immediately released back to atmosphere) to long-term (millennia) storage. The sequestered SOC process should increase the net SOC storage during and at the end of a study to above the previous pre-treatment baseline".

A straightforward approach to consider both soil carbon stocks (Figure 1a) and the time carbon stays out of the atmosphere is to mathematically calculate carbon sequestration as the area under the curve of remaining carbon over time (Sierra et al., 2021), as shown in Figure 1b. When calculated in this way, the units of carbon sequestration are [mass × time], thus describing the amount of carbon retained in the soil over a time horizon. The results in these units allow a more precise comparison of mitigation measures associated with carbon in soils.

Figure 1 shows that at t_1, Measure B reaches a higher SOC stock than Measure A (panel a) and higher SOC sequestration (panel b), but at t_2, even if SOC stock of Measure B is lower than Measure A, the SOC sequestration of Measure B continues to be higher because more carbon was stored in the system over that period. Thus, Figure 1 illustrates contrasting results when time is taken into consideration. A case study and further discussion on the topic can be found in Crow and Sierra (2022).

Carbon sequestration quantified in units of mass multiplied by time has been proposed to address the issue of permanence in carbon trading under the name "ton-year accounting" (Fearnside et al., 2000). This idea has recently been refined by mathematically considering the time carbon spends stored in ecosystems in Sierra et al. (2021). This is more consistent with the definitions of Sedjo and Sohngen (2012) and Olson et al. (2014), and with the global warming

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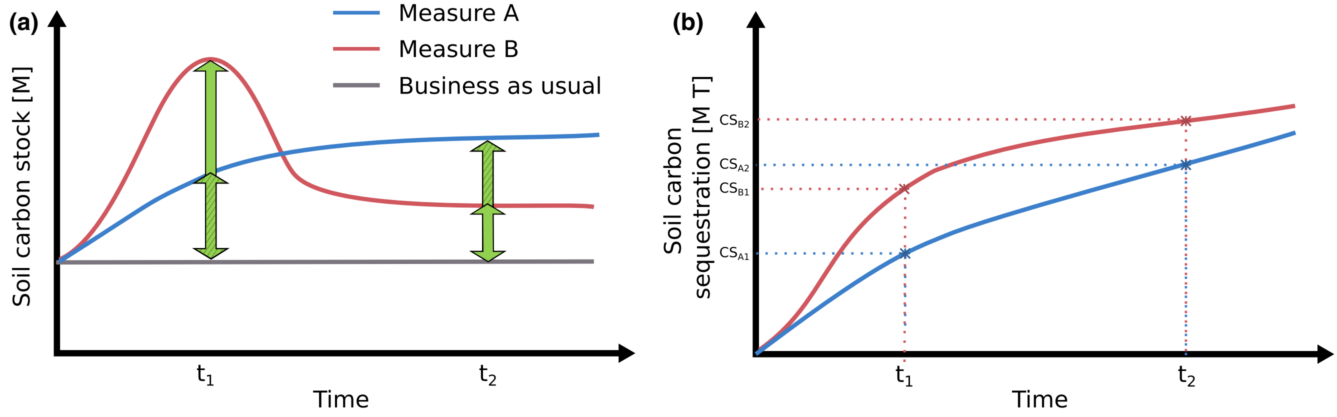

FIGURE 1 Conceptual representation of the effects of implementing two different measures (A and B) to enhance SOC over a time horizon since the implementation of a measure to enhance SOC. (a) SOC stocks [*M*, mass units] and (b) soil carbon sequestration (CS) [*MT*, mass × time units] defined as the area under the curve of remaining carbon over time (integral of curves in panel a). Green arrows in (a) represent the total C sequestration as defined by Don et al. (2023) at times t_1 and t_2 for the measures A and B. $CS_{i,t}$ in (b) indicates the soil carbon sequestration of a measure *i* at a time *t*.

potential concept, which helps to compare the effect of both emissions and sequestration on atmospheric radiative forcing.

The article of Don et al. (2023), contrasted with previous literature, suggests that we are still far from a scientific consensus on a definition of carbon sequestration in soils and natural carbon sinks. However, in the past decade, there has been important progress in field-based quantifications of carbon stocks and fluxes, their persistence, and mathematical models to represent their dynamics. Authoritative institutions like the IPCC or UNFCCC could provide the appropriate venue to reach such a consensus and render policymakers and society at large an appropriate metric to holistically quantify the role of nature-based solutions in climate change mitigation. We are convinced that explicitly including time in the definition of carbon sequestration is key to reach more impactful climate change actions.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

There are no data involved in this letter.

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