10.5281/zenodo.23690869

Soil carbon removals: The impact of non-permanence on climate mitigation

Flora Desmet[1] (Agroscope), Greet Ruysschaert[2] (ILVO), Jan Peter Lesschen[3] (WUR), Jens Leifeld[1] (Agroscope)

- Temporary carbon removals provide climate mitigation benefits but are not suited to claim CO_2 emissions compensation. They are better suited to claim compensation of short-lived CH_4 emissions.
- Temporary carbon removals can contribute to lower global peak warming if the sequestration is maintained long enough, i.e., at least until the time of peak warming. Longer monitoring periods should therefore be encouraged.

Introduction

The permanence of carbon removals in soils by carbon farming cannot be guaranteed, putting at risk the climate integrity of using such removals for CO_2 emissions compensation. In the EU project MARVIC[1] we quantified the impact of non-permanence of carbon removals in soils by carbon farming on climate change mitigation and on the effectiveness of such removals to compensate GHG emissions.

The climate benefit is evaluated based on the avoided energy accumulation in the Earth's system. This corresponds to the cumulative radiative forcing over the period spanning the start of the project to the time horizon[2] at which the climate benefit is evaluated. We also illustrate the impact of different project scenarios on global peak warming in the context of several IPCC emissions pathways.

To illustrate this evaluation, we used four carbon farming project scenarios. All simulate a 10-year activity period during which soil organic carbon (SOC) stocks increase at a rate of 1 tC ha^{-1} yr^{-1} on average, followed by different monitoring periods, namely 5, 30, 90 years, and indefinite, during which the higher SOC stock is maintained. After this monitoring period, the sequestered carbon starts to be re-released. In the scenario with indefinite monitoring period, the carbon remains sequestered permanently. Carbon re-release follows the temporal dynamic of SOC loss observed after conversion from grassland to cropland in Germany [1]. This rather conservative release pathway leads SOC gains to be at 95% reverted in about 185 years.

[1]Monitoring, Reporting & Verification systems for carbon farming in European agriculture, https://www.project-marvic.eu/
[2]Time horizon: length of time until which climate impacts are accounted for.

Funded by the European Union

Grant agreement N° 101112942

Recommendation One: Do not use soil carbon removal units for CO_2 emissions compensation, but rather for short-lived GHG emissions compensation.

The quantification of the climate benefit of soil carbon removals with different monitoring periods shows that i) the benefit depends on the time horizon at which it is evaluated and ii) there is a rapid loss in benefit for monitoring periods shorter than 100 years (Fig. 1). On timescales required for offsetting CO_2 emissions, that is millennia ([2], [3]), more than 87% of the mitigation potential of the sequestration is lost, even for a sequestration that persists 100 years (Fig. 1 right, blue ring). Moreover, a 10-year carbon farming project with subsequent 5 years of monitoring only achieves about half of the mitigation of permanent sequestration at a 100-year horizon (Fig. 1 centre, orange ring). Ensuring the persistence of the sequestration for another 25 years raises the benefit to 74% of permanent sequestration (Fig. 1 centre, purple ring).

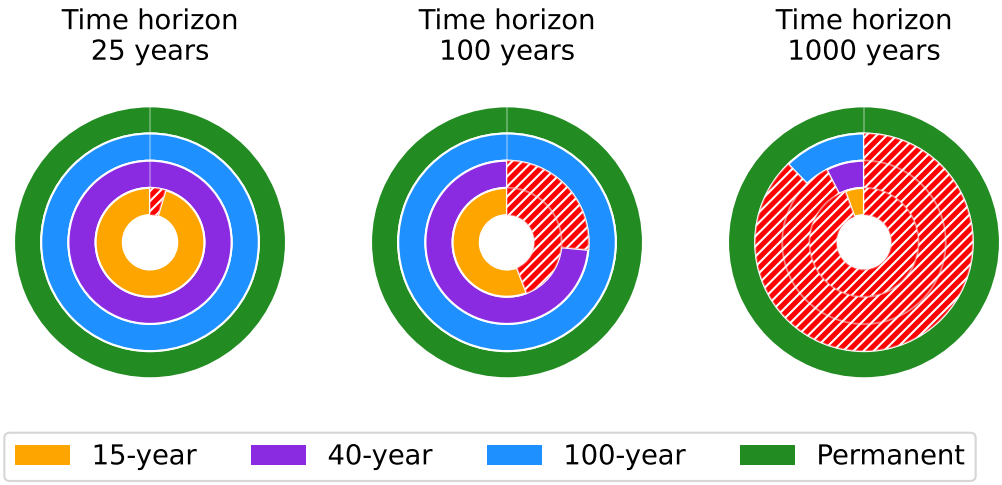


Figure 1. Fraction of climate benefit (in terms of avoided energy accumulation in the Earth's system) achieved by projects with temporary carbon removal relative to a project with permanent removal for 25-, 100- and 1000-year time horizons. Full benefit is represented by a full ring. Colours represent different projects' monitoring periods. Red hatched parts represent the permanency discount that would need to be applied for each combination of monitoring period and time horizon.

In terms of CO_2 emission compensation, this implies that even large permanency discounts (>85%) are not enough to ensure the climate integrity of the compensation on the long-term if the carbon cannot be stored permanently. However, as recently highlighted by two studies ([4], [5]), temporary removals could be better suited to claim CH_4 emissions compensation. Indeed, the increase in temperature induced by an emission of CH_4 only lasts a few decades, better matching the temporality of the temperature response to temporary carbon removals. Furthermore, such compensation would require shorter monitoring periods, which are likely to be more enforceable for carbon farming projects than long-term monitoring requirements.

Recommendation Two: Incentivise project duration of minimum 40 years to ensure lowering global peak warming in a low emissions pathway.

Temporary carbon removals can contribute to lower global peak warming, but its success depends on the duration of the project (activity plus monitoring period), how fast the carbon is released after that project, and on the global emission pathway the world will follow.

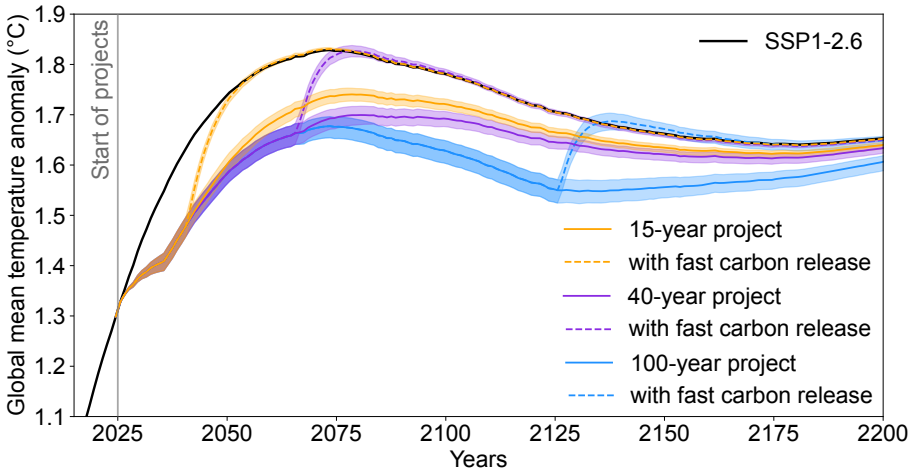


Figure 2. Global mean temperature anomaly (in °C) of SSP1-2.6 (black) and the deviation induced by the carbon farming project scenarios (coloured lines with shading denoting the [25th-75th] uncertainty interval on the temperature response to the project scenarios). Scenarios for which the release of carbon at the end of the monitoring period would happen much faster, namely in about 15 years, are shown as dashed lines. **Note that the magnitude of the deviation from the projects has been increased by a factor 10^{10} compared to a per hectare basis.** This figure should therefore be used as a graphic representation only, solely to understand the temporality of the effects, not their magnitude.

- All project scenarios contribute to lower peak warming in the low emissions pathway (SSP1-2.6) when carbon release happens slowly.
- In case of rapid carbon release that could arise due to wildfire, little stabilised soil carbon, or different pedo-climatic conditions, only projects longer than 40 years (including monitoring period) can contribute to lower peak warming in a low emissions pathway (SSP1-2.6). This is because the benefit of temporary carbon removals on global mean temperature is lost soon after all sequestered carbon has been re-emitted.
- Therefore, projects should sustain at minimum 40 years (including activity and monitoring periods), and longer projects should be incentivised since the world is currently on track for a less optimistic global emissions pathway.
- For medium to high emissions pathways (SSP2-4.5 or SSP3-7.0), the minimum project duration would be 200 years and more than 400 years, respectively, in case of rapid carbon release.
- If temporary units are delivered, one should ensure that they get replaced as they expire in order to generate a sustained benefit on global mean temperature.

Methodology

The radiative forcing induced by the changes in SOC stocks was computed using Impulse Response Functions [6]. The climate benefit in Fig. 1 is defined as the cumulative radiative forcing over the period spanning the start of the carbon farming project to the time horizon at which the benefit is evaluated. It represents how much energy accumulation in the Earth's system is avoided over a given period of time thanks to the project and it uses the same framework as the Global Warming Potential (GWP).

The FaIR model [7] is used to study the impact of the carbon farming project scenarios on global peak warming in the context of different shared socioeconomic pathways (SSPs). The project duration is defined as the sum of the activity and monitoring periods.

The results presented in this policy brief are independent of the chosen accumulation rate of 1 $tC\ ha^{-1}\ yr^{-1}$, which stands at the upper bound of observed accumulation rates in carbon farming.

Unlike the accumulation rate, the timescale of carbon re-release has a significant influence on the results, as shown in Fig. 2. The speed of re-release depends on a number of factors and it is difficult to predict how fast re-release would occur in practice. The climate benefits shown in Fig. 1 would be significantly lower for projects with monitoring periods of 5, 30, and 90 years if the release timescale used for the dashed-line scenarios in Fig. 2 was assumed.

The detailed methodology and complete results are available in [6].

Affiliation of the authors

[1] Climate and Agriculture Group, Agroscope, Zürich, Switzerland
[2] Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Merelbeke-Melle, Belgium
[3] Wageningen Environmental Research, Wageningen University and Research (WUR), Wageningen, Netherlands

References

[1] D. Emde *et al.*, 'The centennial legacy of land-use change on organic carbon stocks of German agricultural soils', Glob. Change Biol., vol. 30, no. 8, p. e17444, 2024, doi: 10.1111/gcb.17444.

[2] M. R. Allen *et al.*, 'Net Zero: Science, Origins, and Implications', Annu. Rev. Environ. Resour., vol. 47, no. 1, pp. 849–887, 2022, doi: 10.1146/annurev-environ-112320-105050.

[3] M. R. Allen *et al.*, 'Geological Net Zero and the need for disaggregated accounting for carbon sinks', Nature, vol. 638, no. 8050, pp. 343–350, 2025, doi: 10.1038/s41586-024-08326-8.

[4] F. Venmans, W. Rickels, and B. Groom, 'Temporary carbon dioxide removals to offset methane emissions', Nat. Clim. Change, vol. 16, no. 1, pp. 37–42, 2026, doi: 10.1038/s41558-025-02487-8.

[5] Y. He *et al.*, 'Temporary carbon dioxide removal to offset short-lived climate forcers', Nature, vol. 654, no. 8118, pp. 391–397, 2026, doi: 10.1038/s41586-026-10607-3.

[6] F. Desmet and J. Leifeld, 'Radiative Forcing of Carbon Farming practices: Insights into climate impacts of non-permanence, greenhouse gas trade-offs, and biogeophysical effects.', Deliverable 4.3 of MARVIC project v1.0, 2025. doi: 10.5281/zenodo.17225589.

[7] N. J. Leach *et al.*, 'FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration', Geosci. Model Dev., vol. 14, no. 5, pp. 3007–3036, 2021, doi: 10.5194/gmd-14-3007-2021.