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Global soil organic carbon sequestration potential under sustainable food systems and climate mitigation

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E-mail: dianti.kamasela.78c@st.kyoto-u.ac.jp**Keywords:** carbon sequestration, climate mitigation, food system, integrated assessment model, soil organic carbonSupplementary material for this article is available [online](#)**Abstract**

Soil organic carbon (SOC) sequestration is a key nature-based solution to mitigate climate change. Previous studies have highlighted its potential and the role of improved management practice, but many relied on static land-use assumptions or limited spatial data, overlooking socio-economic and climate-driven changes that affect land availability. This study assessed the global SOC sequestration potential of cropland and bioenergy land under three land-use pathways: business as-usual (BAU), a sustainable food system (FOOD), and a 2 °C climate target (2°). Our results show that both climate and food policies may influence SOC sequestration through land-use changes. Under the 2 °C scenario, large-scale expansion of bioenergy crops could increase SOC stocks by about 7% (~9 Gt CO₂). In contrast, the FOOD scenario achieves only modest SOC gains, slightly lower than BAU (−1.59 Gt CO₂). This is because dietary shifts reduce pasture demand but do not significantly change cropland area, and bioenergy deployment is limited. While plant-based diets improve food system efficiency and reduce emissions, their SOC benefits are indirect and depend on how freed-up land is used for mitigation, such as afforestation or bioenergy production. Regions with significant bioenergy expansion—such as Latin America, reforming economies, and OECD/EU countries—show the highest SOC gains. Regions with large cropland areas, including the Middle East, Africa, and Asia, contribute 70% of the global potential. Moreover, substantial SOC potential can be realized at a cost below \$100 per ton of CO₂, highlighting SOC sequestration as a feasible and economically viable climate mitigation strategy. Our study findings underscore the trade-offs between food system transformation, land-use efficiency, and carbon storage, and emphasize that climate policies promoting bioenergy expansion can achieve substantial SOC gains, while dietary policies alone have limited impact if without strategic land management.

1. Introduction

The expansion of agriculture in recent decades has significantly altered the global carbon, water, and nutrient cycles. The conversion of natural ecosystems into croplands, pastures, and rangelands has been a major contributor to rising atmospheric carbon dioxide (CO₂) levels. Agriculture and land-use changes together account for approximately 24% of global

greenhouse gas emission [1]. Since the Industrial Revolution, land-use changes have released an estimated 785 GtCO₂ into the atmosphere, with 3.9 GtCO₂ emitted in 2021 alone [2]. Soil organic carbon (SOC) sequestration is increasingly recognized as a promising nature-based method that will contribute to mitigating climate change. SOC captures atmospheric CO₂ and stores it in stable soil carbon pools. Given that soils store two to three times more carbon than



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the atmosphere, even modest increases in SOC stocks can lead to significant reductions in atmospheric CO₂ concentrations [3, 4].

Many studies have demonstrated the potential of enhancing SOC through improved land management using methods such as conservation tillage, cover cropping, crop rotation, and organic amendments to increase SOC levels [3–6]. For example, Minasny *et al* [4] proposed that increasing global SOC stocks by 0.4% (4‰) per year could sequester 2–3 GtCO₂ annually [3]. Similarly, Zomer *et al* [3] projected that up to 137 GtCO₂ could be sequestered over 20 years using around 1600 million ha of cropland, which is equivalent to about 6.7 GtCO₂ per year [4] (figure 1). Other studies have estimated global SOC sequestration potential within the range of 2.5–5.6 GtCO₂ per year, depending on management practices and supporting strategies [7]. However, many of these assessments have relied on static land-use assumptions or limited spatial data, neglecting dynamic socio-economic and climate-driven changes that influence the availability of land for SOC sequestration.

The availability of land for SOC sequestration is influenced by location, land-use pathways, and the types of mitigation strategies implemented. Climate policies, for example, may redirect land from food to energy production, constrain agricultural expansion to preserve high-carbon ecosystems, shift production toward less emissions-intensive commodities, or promote emission-efficient management such as optimized fertilizer use or reduced livestock density. While such measures mitigate emissions, they also indirectly affect crop production, land prices, and the total area of cropland [8–14]. Reductions in cropland through afforestation or bioenergy expansion may further constrain SOC enhancement opportunities [5, 15]. Simultaneously, food-system policies—particularly dietary shifts—offer a ‘double climate dividend’ by reducing emissions and freeing land for climate-focused purposes [16–19]. For example, reduced livestock production under dietary change scenarios can lower grassland demand and increase opportunities for SOC sequestration on newly available cropland. Moreover, considering future land use for SOC sequestration program is essential to avoid over- or underestimating its potential and prevent disruptions to ongoing management practices that could release stored carbon back into the atmosphere.

Despite these promising insights, critical gaps remain. Most global SOC assessments have not fully accounted for dynamic land-use changes under future climate and socio-economic scenarios, nor have they comprehensively evaluated the cost-effectiveness of SOC practices at a global scale. This study addresses these gaps by quantifying global SOC sequestration potential under three land-use pathways—business-as-usual (BAU), sustainable food system (FOOD), and a 2 °C climate target (2°)—using the maximum management practices

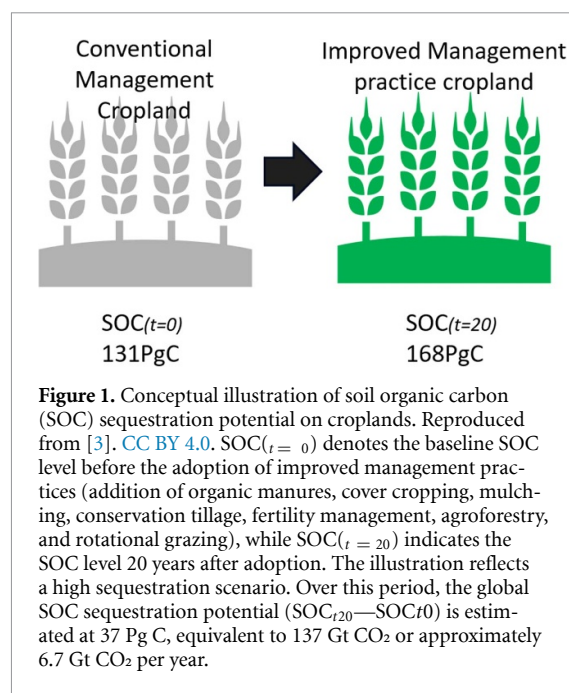


Figure 1. Conceptual illustration of soil organic carbon (SOC) sequestration potential on croplands. Reproduced from [3]. [CC BY 4.0](#). $SOC_{(t=0)}$ denotes the baseline SOC level before the adoption of improved management practices (addition of organic manures, cover cropping, mulching, conservation tillage, fertility management, agroforestry, and rotational grazing), while $SOC_{(t=20)}$ indicates the SOC level 20 years after adoption. The illustration reflects a high sequestration scenario. Over this period, the global SOC sequestration potential ($SOC_{20}-SOC_{t0}$) is estimated at 37 Pg C, equivalent to 137 Gt CO₂ or approximately 6.7 Gt CO₂ per year.

identified by Zomer *et al* [3] and Minasny *et al* [4], consistent with IPCC guidelines [3, 4, 9] and other studies [5, 20–23]. In treating land-use changes, only areas that persist until 2100 for SOC sequestration program were considered for SOC calculations. Furthermore, we provide a supply-curve-based cost assessment, integrating improved management practices with land-use dynamics, to offer actionable insights for leveraging SOC sequestration as a scalable climate mitigation strategy.

2. Methods

2.1. Overview

Our study framework employed the Asia-Pacific Integrated Model-Hub (AIM-Hub) [16, 24] to assess land requirements for crops, grasslands, bioenergy, and forests under multiple land-use scenarios. The resulting regional land-demand data were integrated into the AIM Platform for Land-Use and Environmental Modeling (AIM-PLUM) [25], where land allocation was conducted through profit maximization (figure 2). Land productivity inputs were derived from the Vegetation Integrative Simulator for Trace Gases (VISIT) [26] and Global Agro-Ecological Zoning (GAEZ) models. To ensure environmental sustainability, protected areas were excluded from the allocation process.

Reference soil carbon stocks (SOC_{ref}) for the year 2010 were used, derived from VISIT model [26]. This represents the natural net balance of carbon inputs and outputs in the soil under Shared Socioeconomic Pathway 2 (SSP2)-RCP4.5, which is shaped by a variety of factors, including plant growth, litterfall, and microbial activity, which are in turn influenced by abiotic factors such as temperature, precipitation, and

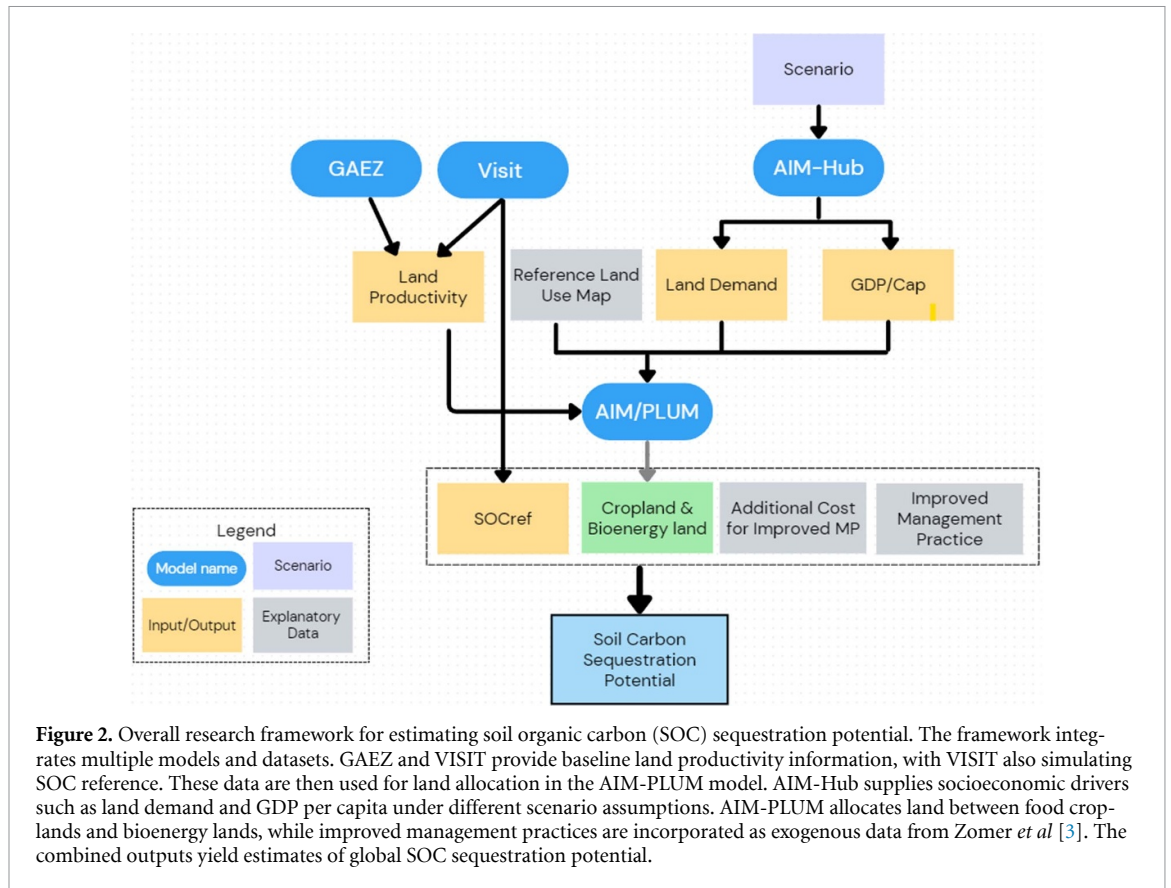


Figure 2. Overall research framework for estimating soil organic carbon (SOC) sequestration potential. The framework integrates multiple models and datasets. GAEZ and VISIT provide baseline land productivity information, with VISIT also simulating SOC reference. These data are then used for land allocation in the AIM-PLUM model. AIM-Hub supplies socioeconomic drivers such as land demand and GDP per capita under different scenario assumptions. AIM-PLUM allocates land between food croplands and bioenergy lands, while improved management practices are incorporated as exogenous data from Zomer *et al* [3]. The combined outputs yield estimates of global SOC sequestration potential.

atmospheric CO₂ concentration. These factors are incorporated into the VISIT model through parameterization or calibration against observed ecosystem data. Finally, carbon sequestration was calculated by multiplying SOC_{ref} by the allocated area and the management practice applied (r). The explanation of models logic can be seen in supplementary information.

2.2. Land allocation mechanism

Land-use projections for cropland, grassland, bioenergy, and forests were obtained from AIM-Hub [24, 27], a computable general equilibrium model widely used in climate and land-use studies [15, 19, 25, 28, 29]. It represents economic behavior through supply, demand, trade, and investment functions influenced by population growth, GDP, and technology.

Aggregated regional land-demand data were transferred to AIM-PLUM, which downscales land allocation to $0.5^\circ \times 0.5^\circ$ grid cells [25]. Allocation is based on profit maximization under biophysical and economic constraints—such as productivity (from GAEZ/VISIT), irrigation maps, land conversion costs, and carbon pricing. Protected areas (mainly forests) were excluded from allocation [30, 31].

Pasture area was adjusted around its base-year distribution due to limited future profit data for livestock production, ensuring consistency with total pasture requirements while minimizing development costs.

In treating land-use changes, only cropland and bioenergy areas that persist until 2100 were considered for SOC calculations. Grid cells undergoing land-use change were excluded, even if previously classified as cropland or bioenergy, while new expansions were included.

2.3. SOC sequestration

The soil carbon sequestration formulas (Q.1) and (Q.2) estimates is adopted from Roe *et al* [5]. This formula is introduced from Soils Revealed [32] which calculates the annual rate of change in SOC stocks based on Tier 1 stock difference approach [1], to develop new estimates of technical potential. The data used for SOC_{ref} is driven from VISIT model under the SSP2 land-use pathway and RCP4.5 climate condition in year 2020.

For the technical potential, SOC is defined relative to the reference SOC stock (SOC_{ref}) for a given location by a combination of linear SOC modifying factors for land use $LA_{(l,t)}$ and management practice, which in this study define as (r). Thus, Δ SOC will be non-zero only if at (r) differs between the start and end of the accounting period.

In condition of SOC_{ref}, r is set as conventional management practice, where current cropland was assumed to represent conventional tillage everywhere, and input was defined as low where >50% of crop residues are used as animal forage based on Wiersenius [21] or where >50% of area harvested

is allocated to vegetable or fiber crops according to Monfreda *et al* [22].

In SOC_t , r represents the maximum improvement factor for management practices, corresponding to the highest SOC sequestration potential can be achieved as reported by Zomer *et al* [3] and Lefebvre *et al* [20] (see supplementary information figure S5),

$$SOC_t = SOC_{ref} \times r \times \frac{44}{12} \times LA_{(l,t)} \quad (Q.1)$$

$$\Delta SOC = SOC_t - SOC_{ref}. \quad (Q.2)$$

2.4. SOC sequestration costs

SOC sequestration costs were separated from crop and livestock production costs and cropland transition costs. The latter includes expenses related to crop cultivation, including seeds, fertilizers, labor, water, and machinery, which are fundamental costs incurred regardless of SOC sequestration objectives. In contrast, SOC sequestration costs represent additional expenditures specifically dedicated to enhancing SOC levels.

Estimating the total cost of increasing SOC through improved management practices remains a challenge due to limited data on current agricultural practices. Therefore, following the method of Roe *et al* [5], we assumed conventional tillage and low input as the baseline management system.

Then, the cost data were obtained from Sperow [33]. This study estimated the marginal cost of SOC sequestration by combining potential SOC increases, with existing payment schemes designed to promote no-tillage adoption. This approach is illustrated in a case study from the USA (figure S6). The estimated costs reflect the amount of SOC that can be sequestered through no-tillage and the expected expenses incurred by landowners when transitioning from conventional tillage to no-tillage practices. This cost been including implementation costs (equipment, rental, cover crop seeds, fertilizers), supporting practices (crop rotation, residue management), financial assistance schemes (advance payments or reimbursements) and Region-specific details, contract durations (3–5 years), and occasionally adoption status. Sequestration costs varied depending on the method and region, typically ranging from USD \$10 to USD \$100 per ton of CO_2 [33–35]. We adopted a median value of USD \$50 per ha as the additional cost for implementing no-tillage farming in the USA. This cost then added by monitoring, reporting, and verification cost Brummitt *et al* about $7.5\$ \text{ ha}^{-1} \text{ yr}^{-1}$ [36]. To account for regional economic disparities, these costs were adjusted and allocated across global regions based on gross domestic product per capita estimates (SI Note3, table S4,7).

To estimate the carbon sequestration supply curve, we conducted a spatially explicit cost analysis

[17, 37, 38]. We first calculated the per-unit cost of SOC sequestration for each 0.5° grid cell. Then, for each carbon price level, the total supply was derived by summing the amount of carbon sequestered in all grid cells where the marginal cost remained below the given price threshold. The supply curve was constructed by iteratively adjusting the carbon price and aggregating the corresponding sequestration potentials.

2.5. Scope and limitations

There are several points need to be noted in this study as scope and limitations. First, we considered two land types for SOC analysis: cropland and bioenergy land. Cropland includes all food and feed production areas, while bioenergy land refers to croplands cultivated with perennial bioenergy grasses—specifically *Miscanthus* and *switchgrass*—used as proxies for dedicated bioenergy crops [17]. However, our current AIM-PLUM model allocates bioenergy land were based on bioenergy demand and average yield production for both *Miscanthus* and *switchgrass*. Specific land allocation for each type bioenergy land is not determined.

Second, for existing croplands, conventional tillage was assumed, and fertilizer input factor was applied to represent low-input systems [5]. In reality, some regions have already adopted no-tillage or medium- to high-input systems, but reliable spatial data on their distribution are lacking. This uncertainty also affects SOC cost estimates, as cost calculations typically assume a transition from conventional to improved practices. In regions where improved practices are already implemented, marginal costs may differ, complicating assessments of the true economic potential and feasibility of large-scale SOC sequestration.

Third, although climate feedbacks—such as warming- or cooling-induced effects on biomass production and SOC sequestration—can influence carbon dynamics [39], they were not explicitly considered in this study. Incorporating additional feedbacks, such as temperature-accelerated SOC decomposition, would fundamentally modify the modeling framework and underlying assumptions, including those related to land allocation, crop yield responses, and SOC turnover. Capturing these processes would require a fully coupled climate–carbon cycle feedback model, which is beyond the scope of the present analysis.

2.6. Scenario settings

This study explored global SOC sequestration potential under BAU, FOOD, and 2° . Each pathway was framed according to SSP2, which is a ‘middle-of-the-road’ scenario that assumes moderate challenges for climate adaptation and mitigation [40]. SSP2

Table 1. Scenario settings.

Scenario name	Pathway
Business as usual (BAU)	Current land-use trends are assumed to continue without major changes, providing a baseline for comparison.
Climate mitigation (Climate policy-2°)	Land allocation is set to limit cumulative CO ₂ emissions below a 2 °C temperature increase, targeting a cumulative cap of 500 Gt CO ₂ after 2020 for a 50% chance of limiting warming to 1.5 °C.
Sustainable food system (Food policy-FOOD)	Food production is balanced with ecosystem health and climate goals through the implementation of dietary shifts, food-waste reduction, and advances in food trade and technology. A shift towards more plant-based diets is assumed, in line with the EAT-Lancet recommendation to cut red meat and sugar intake by 50% by 2050, and daily Food demand is limited to 2503 kcal per capita [42]. This approach aligns with the SDG 12.3 goal of halving global Food waste by 2030 [17, 19, 43]. For the BAU and 2° scenarios, we used standard trade elasticities from the AIM-Hub model under Shared Socioeconomic Pathway 2 (SSP2). For the FOOD scenario, we adopted SSP1 settings, representing a more globalized economy with fewer trade barriers and higher growth in irrigation technology (0.6% per year), increasing yields in both rain-fed and irrigated crops [44].

assumed ongoing trends in socioeconomic and technological development without additional pressures from climate impacts or policies [17, 19, 41]. Each land-use pathway was associated with a value of r (SOC sequestration rates) [3, 20] (figure S2). SOC management factors before 2030 were set conservatively, indicating that current conventional practices have limited carbon sequestration potential [5]. These scenarios illustrate the range of possibilities for enhancing SOC, from current practice to advanced management practices that significantly boost carbon sequestration. The scenario designs are explained in table 1.

3. Results

3.1. Global SOC sequestration under the FOOD or 2° scenarios

Global cropland SOC sequestration potential was strongly influenced by land-use transitions under different policy scenarios. Our analysis indicates that implementing climate policies under the 2° scenario could increase cumulative global SOC sequestration potential to 148 GtCO₂ by 2100 (figure 3(A)). This increase was primarily driven by the expansion of bioenergy land, which supports SOC accumulation through improved management and fallowing. In contrast, the FOOD policy slightly reduced SOC potential, reaching 137 GtCO₂, comparable to 139 GtCO₂ under BAU.

During the base years (2010–2020), conventional land management practices were assumed, resulting in very low SOC sequestration. Following the adoption of improved practices, annual SOC sequestration increased sharply by 2030, peaking at approximately 3–4 GtCO₂ yr⁻¹ during the first two decades. It then gradually declined to 1–2 GtCO₂ yr⁻¹

as soils approached saturation, stabilizing at 0.5–1 GtCO₂ yr⁻¹ after 50 years (figure 3(B)). This temporal pattern highlights the finite capacity of soils to store carbon and underscores the importance of early intervention.

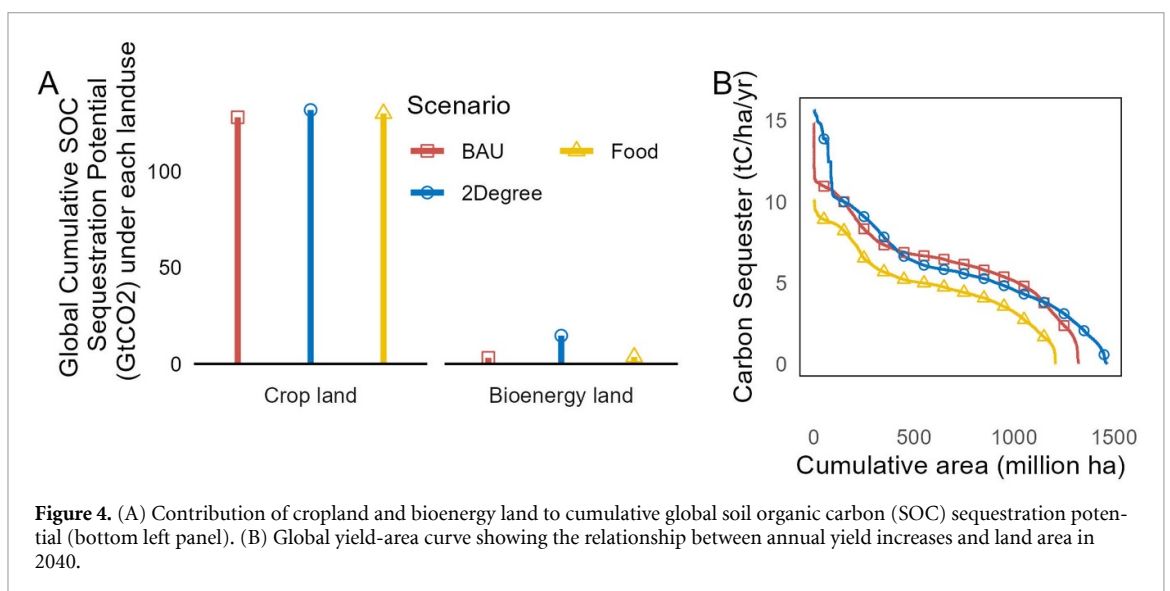
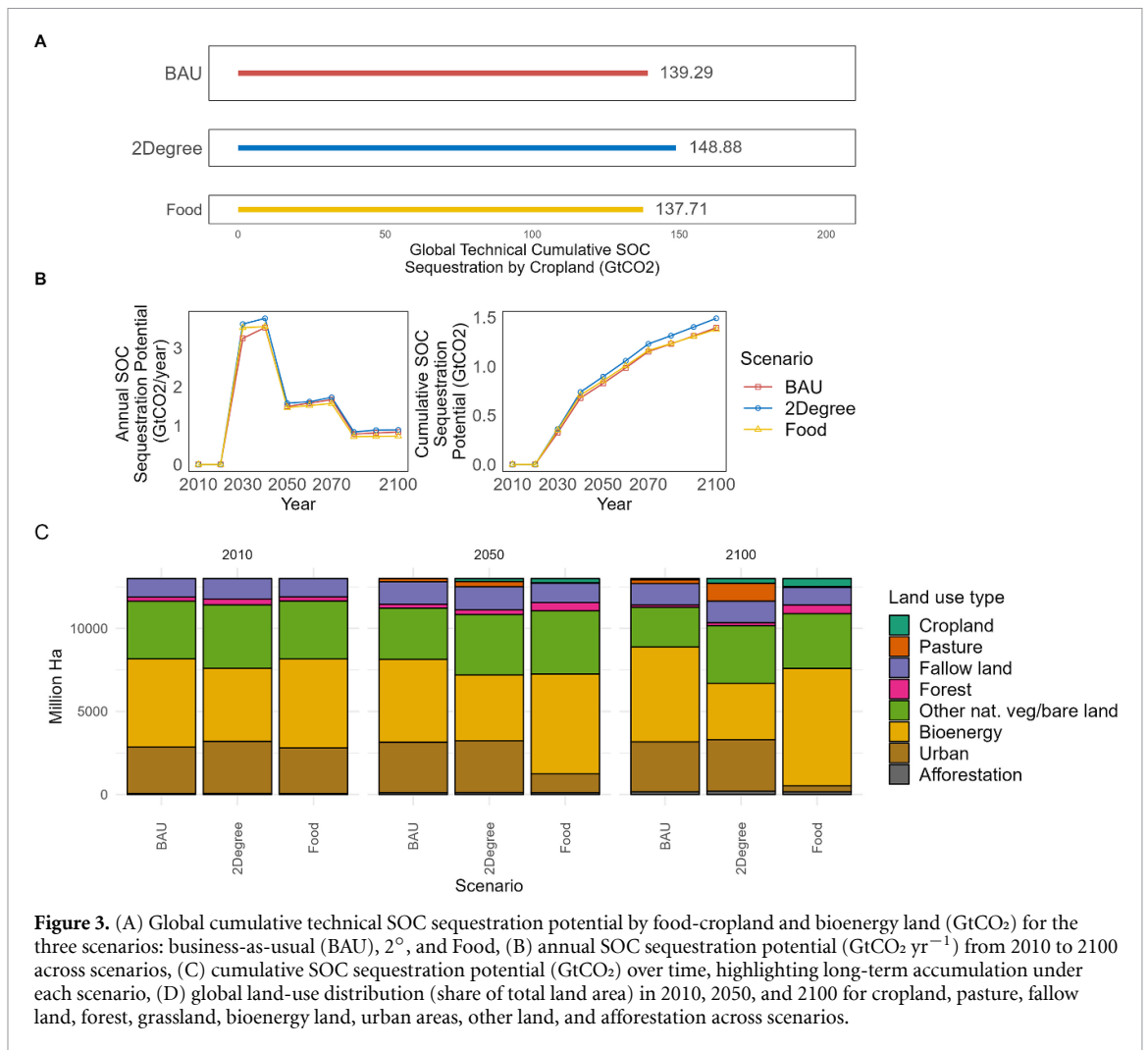
Cropland consistently contributed the largest share of SOC potential across all scenarios, with similar values for each scenario. Differences among scenarios were driven primarily by bioenergy land expansion, which was substantial under 2° but modest under BAU and FOOD. The total land available for SOC sequestration was approximately 1300 Mha under FOOD, 1550 Mha under BAU, and 1700 Mha under 2° (figure 4(A, B)).

3.2. Cost and regional potential

The annual supply curves for SOC sequestration potential under different scenarios in 2030 (20 years after the adoption of improved management practices) can be seen in figure 5(B). The curves highlight the additional costs required to enhance SOC levels. Both the FOOD and BAU scenarios caused a leftward shift in the supply curves, indicating slightly higher marginal costs per unit of carbon sequestered.

At a carbon price of USD \$100/tCO₂, approximately 3.5 GtCO₂ yr⁻¹ of SOC sequestration was achievable under the 2° scenario. This potential decreased slightly to 3.44 GtCO₂ yr⁻¹ under BAU and further to 3.42 GtCO₂ yr⁻¹ under the FOOD scenario. These shifts reflect trade-offs between policy objectives and total SOC sequestration potential.

These results align with findings by Sperow [33], which show that a large portion of SOC sequestration potential (64%–93%) can be achieved at relatively low cost, supporting the cost-effectiveness of enhanced cropland management practices as a climate mitigation strategy.



From a regional perspective, most countries experienced changes in SOC sequestration potential under the FOOD and 2° scenarios, with the 2° scenario showing the strongest effect (figure 5(A)). Under 2°, regions such as Reforming Economies, Latin America, and OECD & EU countries exhibited

increased SOC potential, primarily driven by land-use changes that prioritize carbon mitigation, including bioenergy expansion.

In contrast, under the FOOD scenario, Reforming Economies, Latin America, and OECD & EU countries were projected to experience slightly reduced

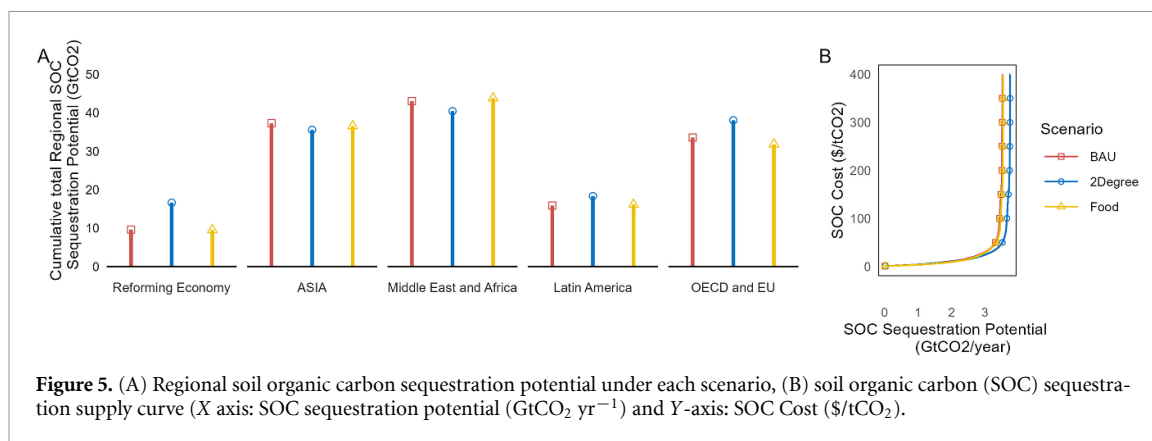


Figure 5. (A) Regional soil organic carbon sequestration potential under each scenario, (B) soil organic carbon (SOC) sequestration supply curve (X axis: SOC sequestration potential (GtCO₂ yr⁻¹) and Y-axis: SOC Cost (\$/tCO₂).

SOC potential, likely due to stricter land-use constraints associated with food-waste reduction.

4. Discussion

4.1. SOC increase under climate policy driven by bioenergy expansion

Our results show that both food and climate policies strongly influence land-use transitions, which in turn shape global SOC sequestration potential. In the 2 °C scenario, which prioritizes climate mitigation, substantial bioenergy expansion occurs, contributing approximately 7% additional SOC potential (cumulatively) (9 Gt CO₂). This highlights the important role of bioenergy lands in enhancing SOC stocks (figure 3(A)) and suggests that climate-focused land-use policies can achieve greater SOC sequestration [12, 15, 29, 45].

These findings are consistent with Xu *et al* [46], who reported that cultivating energy crops on marginal lands can increase SOC sequestration by 7.1%–16%. Accordingly, climate policies that expand bioenergy areas could enhance carbon sequestration, as long as the carbon losses from land-use change do not outweigh the gains. Optimizing both above-ground biomass (for bioenergy production) and belowground biomass (for SOC enhancement) with careful crop selection and targeted deployment within suitable climatic zones [39].

Despite its mitigation potential, the sustainability of bioenergy SOC sequestration also depends on its cropping systems. Switchgrass and Miscanthus, the two leading perennial bioenergy crops, are often promoted for cultivation on marginal lands; however, their respective effects on SOC sequestration and stabilization can differ substantially. In this study, as declare in the scope and limitation, bioenergy lands were treated similarly to croplands, using average yield data from both species as estimated by the H08 model (SI Note2) [17]. Based on these average yields and bioenergy demand under the 2 °C climate policy scenario, we allocated the total area of bioenergy land. However, the allocation among specific crop types was not differentiated, our estimates

represent an approximation of total SOC change resulting from land expansion only. Previous studies have shown significant crop-specific differences—Miscanthus, for instance, generally achieves greater SOC enhancement than switchgrass [46]. The actual SOC gains could vary depending on the relative share of Miscanthus and switchgrass. Thus, a more accurate assessment of SOC gains associated with bioenergy cropland can be achieved by explicitly considering the species of bioenergy crops in future study.

While bioenergy expansion can enhance SOC over the long term, short-term carbon losses from land-use conversion—particularly from natural ecosystems—may temporarily offset these benefits [11, 13]. Moreover, the permanence of SOC gains is uncertain and contingent on continued land management and crop rotation practices. Therefore, climate policies promoting large-scale bioenergy deployment must carefully balance the carbon benefits against potential food security and biodiversity trade-offs, ensuring that bioenergy expansion contributes to sustainable and resilient mitigation pathways.

4.2. SOC potential is slightly reduced under the FOOD policy

Under the FOOD scenario, cumulative SOC gains were modest compared to BAU, primarily due to minimal changes in cropland area. Because this scenario mainly targets red meat reduction—which affects pastureland rather than cropland—the total cropland area remains largely similar to BAU [16, 17]. Moreover, bioenergy land allocation is lower under FOOD than in the 2 °C scenario, thereby limiting additional SOC gains (figure 3(C)). Although the scenario promotes greater consumption of plant-based proteins such as legumes, nuts, and seeds, some of these crops are relatively land-intensive [47], leading to increased allocation for specific types of plant-based protein production. In contrast, food-waste reduction and trade openness under the FOOD scenario encourage cropland intensification, improving land-use efficiency and reducing the need for cropland expansion [5, 15, 19, 28]. As a result, total SOC potential slightly decreases (−1.59 Gt CO₂).

Nevertheless, the FOOD scenario can still contribute indirectly to SOC accumulation if freed-up land is redirected toward mitigation options such as afforestation or sustainable bioenergy production [17]. This outcome illustrates a potential trade-off between dietary-based emission reduction and soil carbon sequestration: while dietary shifts effectively reduce methane emissions from livestock, they may not substantially enhance SOC storage due to limited cropland expansion and reduced bioenergy deployment.

Overall, the FOOD scenario underscores the complex interactions between dietary transitions, land-use efficiency, and soil carbon dynamics. Although reduced meat consumption and improved food system efficiency lower total agricultural emissions, SOC gains remain modest without significant land-use change. The long-term sustainability of this pathway depends on whether freed-up land is managed to deliver additional carbon benefits, particularly through afforestation or bioenergy integration under coherent land-use and food policies [16, 17].

4.3. Regional insight

Regional SOC potentials varied substantially under different scenarios (figure 5(B)). Under 2°, regions with large bioenergy expansion—reforming economies, Latin America, and OECD/EU countries—showed higher SOC potential [35, 48]. By contrast, under FOOD policy, reforming economies, Latin America, and OECD/EU countries experienced a decline due to dietary shifts, food-waste reduction, and limits on cropland expansion. These policies reduce agricultural emissions and improve land-use efficiency, but efficiency gains can limit cropland availability for SOC, highlighting a trade-off between food and climate objectives [16, 17, 19].

The Middle East and Africa consistently demonstrated the highest SOC potential likely due to land restoration and sustainable agricultural practices. Africa, with vast underutilized arable land (~60% of the world's remaining uncultivated land), holds the greatest SOC potential if managed sustainably. Asia, with ~590 Mha of cropland, contributes significantly (~35 GtCO₂-eq) to global SOC sequestration. In OECD countries, SOC-enhancing practices are more cost-efficient due to advanced technology, infrastructure, and policy support, whereas developing countries face constraints such as limited capital, labor, and land tenure security [12, 49–54].

Our supply curve analysis shows that a large portion of SOC potential can be realized at relatively low cost (figure 5(A)), supporting the economic feasibility of improved cropland management as a climate mitigation strategy Sperow [33]. At a carbon price of USD \$100/tCO₂, the 2° scenario can achieve ~1.48 GtCO₂ yr⁻¹, compared to 1.3 GtCO₂ yr⁻¹ under FOOD and 1.25 GtCO₂ yr⁻¹ under BAU.

Advanced technologies—such as precision agriculture, remote sensing, and automated fertilization—further enhance cost-efficiency, particularly in OECD countries. Although the implementation cost per hectare (\$/ha) is generally higher in OECD countries (Supplementary Information, table S4), the cost per ton of CO₂ sequestered (\$/tCO₂) can be lower. This occurs because higher sequestration potential per hectare offsets the greater per-hectare costs, reducing the effective cost per ton of carbon sequestered Sperow [33].

4.4. Comparison to past studies

Compared to other studies, our simulation suggests that improved soil management could sequester approximately 3–4 GtCO₂ yr⁻¹ during the first 20 years. This is slightly lower than the estimate by Zomer *et al* [3], who projected up to 6.8 GtCO₂ yr⁻¹, mainly due to differences in assumed cropland area. Zomer *et al* used a global cropland estimate of 1600 Mha, whereas our model assumed around 1300 Mha (figure 3), with a gradual increase over time. On average, our results indicate a sequestration potential of 1.62–1.82 GtCO₂ yr⁻¹, broadly consistent with Minasny *et al* [4], who estimated 2–3 GtCO₂ yr⁻¹ under the 4‰ initiative, assuming feasible regional implementation and widespread adoption of best practices. Our estimates are also comparable to other studies, including Paustian *et al* [50], Smith *et al* [51], Sommer and Bossio [55], Batjes *et al* [56], and Lal *et al* [57] (SI, table S3).

Compared to the FAO GSOCseq report (2022), we also created a soil carbon sequestration map from this study (figure S4) and compare to FAO [58]. Our maps appear largely similar across scenarios because the same SOC increment target was applied. The main differences lie in spatial distribution, which varies slightly depending on land allocation between cropland and bioenergy. In contrast, the FAO report's distribution depends on the input scenario (SSM1–3).

5. Conclusion and recommendation

This study evaluated the global SOC sequestration potential of cropland and bioenergy land under three major land-use pathways: BAU, a sustainable food system (FOOD), and a 2 °C climate target (2°). Our results show that both climate and food policies influence global SOC sequestration primarily through their effects on land-use dynamics.

Under climate-focused policies (2 °C scenario), substantial expansion of bioenergy crops can increase SOC stocks by approximately 7% (~9 Gt CO₂), highlighting the important role of bioenergy lands in long-term carbon storage. SOC gains, however, are sensitive to crop selection, land allocation, and previous land-use type. Among bioenergy crops,

Miscanthus generally provides greater SOC enhancement than switchgrass. Beyond meeting energy demand, this emphasizes the importance of this crop type specific management for realizing SOC benefits—a factor not fully considered in our study. Future research should therefore explore targeted allocation of bioenergy crop types rather than treating bioenergy land as homogeneous.

In contrast, the FOOD scenario generates only modest SOC gains, slightly lower than BAU (−1.59 Gt CO₂), mainly because dietary shifts reduce pasture demand without substantially affecting cropland area, and bioenergy deployment remains limited. While plant-based diets improve food system efficiency and reduce emissions, their impact on SOC is indirect and depends on whether freed-up land is used for mitigation strategies such as afforestation or bioenergy production.

Overall, these findings underscore the trade-offs between food system transformation, land-use efficiency, and carbon sequestration. Climate policies that actively promote bioenergy expansion can substantially enhance SOC, whereas dietary policies alone provide limited SOC benefits unless combined with strategic land management.

Data availability statements

This study provides the analysis code used to generate the figures presented in both the main text and the supplementary information for reference purposes, which can be freely accessed at https://github.com/hanadianti/Ranalysis_SoilCS.git. The data supporting the findings related to Soil carbon sequestration potential are available upon reasonable request from the corresponding author. Due to privacy, data size and confidentiality considerations, the underlying research data cannot be shared publicly.

The land use demand and allocation used in this study are provided by the AIM-Hub and AIM-PLUM models, which can be accessed at: <https://github.com/KUAtmos/AIMHubdoc> and <https://github.com/KUAtmos/AIMPLUM>.

Supplementary data 1 available at <http://doi.org/10.1088/1748-9326/ae2637/data1>.

Supplementary data 2 available at <http://doi.org/10.1088/1748-9326/ae2637/data2>.


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Conflict of interest


The authors have no competing interests to declare relevant to this article's content.

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