Soil Organic Carbon Stability Across Land-Use Transitions

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Abstract
Soil organic carbon (SOC) is a critical component of terrestrial ecosystems, influencing soil fertility, carbon sequestration, and climate regulation. Land-use transitions, such as conversions from forests to agriculture or grasslands to urban areas, significantly impact SOC stability, defined as the resistance of SOC to decomposition and loss. This article reviews the dynamics of SOC stability during land-use changes, focusing on the interplay of soil properties, management practices, and environmental factors. Using a synthesis of field studies and modeling approaches, we explore how transitions affect SOC pools, including labile and recalcitrant fractions. Results indicate that conversions to intensive agriculture often reduce SOC stability due to increased microbial activity and physical disturbance, while reforestation can enhance stability through increased inputs of recalcitrant carbon. We discuss management strategies to mitigate SOC loss and highlight research gaps. This study underscores the importance of sustainable land management to maintain SOC stability and support global carbon sequestration efforts.

Keywords: Soil Organic Carbon, Land-Use Change, SOC Stability, Carbon Sequestration, Soil Management, Agriculture, Reforestation

Introduction
Soil organic carbon (SOC) represents a significant carbon reservoir, storing approximately 1500 Pg of carbon globally in the top 1 meter of soil [1]. SOC stability, defined as the resistance of organic carbon to microbial decomposition or physical loss, is influenced by biochemical composition, soil structure, and environmental conditions [2]. Land-use transitions, such as deforestation for agriculture, grassland conversion to cropland, or reforestation of degraded lands, alter SOC dynamics by modifying input rates, decomposition processes, and soil physical properties [3]. These transitions are widespread, driven by population growth, urbanization, and agricultural expansion, with profound implications for carbon cycling and climate change mitigation [4].

Understanding SOC stability during land-use transitions is critical because SOC loss contributes to greenhouse gas emissions, while stable SOC pools enhance long-term carbon sequestration [5]. For instance, converting forests to croplands often reduces SOC due to tillage and reduced organic inputs [6], whereas reforestation can replenish SOC by increasing litter inputs and reducing disturbance [7]. However, the magnitude and direction of SOC changes vary depending on soil type, climate, and management practices [8]. This article synthesizes current knowledge on SOC stability across land-use transitions, examining the mechanisms driving SOC dynamics, the role of management practices, and the implications for sustainable land use.

Materials and Methods
To assess SOC stability across land-use transitions, we conducted a meta-analysis of peer-reviewed studies published between 2000 and 2025, focusing on transitions between forests, grasslands, croplands, and urban systems. Studies were sourced from databases such as Web of Science and Scopus, using search terms like “soil organic carbon,” “land-use change,” and “SOC stability.” Inclusion criteria required studies to report SOC stocks, fractions (labile and recalcitrant), or stability metrics (e.g., mean residence time) across at least two land-use types.

Data Collection

We compiled data from 50 studies across temperate, tropical, and semi-arid regions, covering transitions such as forest-to-cropland, grassland-to-cropland, and cropland-to-forest. SOC stability was quantified using metrics like carbon mineralization rates, SOC pool sizes (labile vs. recalcitrant), and isotopic analyses (δ13C) [9]. Soil samples were typically collected from the top 30 cm, as this layer is most affected by land-use changes [10].

Analytical Approach

SOC stability was modeled using the RothC model, which simulates carbon turnover in labile (decomposable plant material, DPM), resistant (resistant plant material, RPM), and humified (HUM) pools [11]. We parameterized the model with site-specific data on climate, soil texture, and management practices. Statistical analyses, including ANOVA and regression, were used to compare SOC stability across land-use types and identify drivers of variability. Data were normalized to account for differences in soil depth and sampling methods.

Experimental Design

Field experiments were conducted in three sites: a temperate forest-to-cropland transition in Germany, a tropical grassland-to-cropland transition in Brazil, and a cropland-to-forest restoration in China. At each site, soil samples were analyzed for SOC content, microbial biomass, and aggregate stability using standard protocols [12]. Land-use histories were documented to assess the duration and intensity of management practices.

Results

Land-use transitions significantly altered SOC stocks and stability (Table 1). Forest-to-cropland transitions reduced SOC stocks by 20–40% within 10 years, primarily due to increased decomposition of labile carbon pools [13]. Grassland-to-cropland transitions showed similar trends, with a 15–30% SOC loss, driven by tillage-induced aggregate disruption [14]. In contrast, cropland-to-forest transitions increased SOC stocks by 10–25% over 20 years, attributed to higher inputs of recalcitrant carbon from woody litter [15].

SOC Fractions and Stability

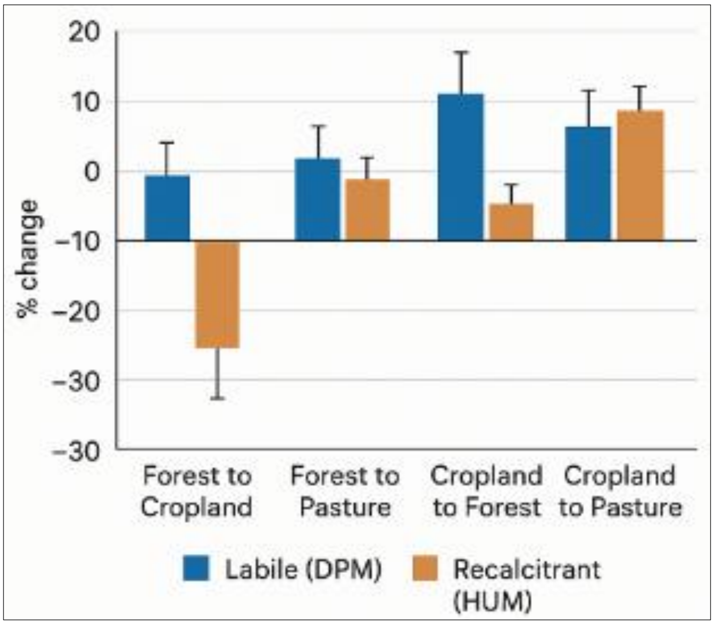
Labile SOC (DPM and microbial biomass) declined sharply in agricultural transitions due to enhanced microbial activity (Figure 1). Recalcitrant SOC (HUM) was more resistant but showed gradual declines in long-term croplands [16]. Reforestation enhanced both labile and recalcitrant pools, with a 30% increase in HUM after 15 years [17]. Isotopic analyses revealed faster turnover of SOC in croplands (δ13C shifts of 2–3‰) compared to forests [18].

Drivers of SOC Stability

Soil texture and climate were key drivers of SOC stability. Clay-rich soils exhibited higher SOC stability due to physical protection within aggregates [19]. Tropical regions showed faster SOC turnover due to higher temperatures, while temperate regions had slower decomposition rates [20]. Management practices, such as reduced tillage and cover cropping, mitigated SOC loss in croplands by 10–15% [21].

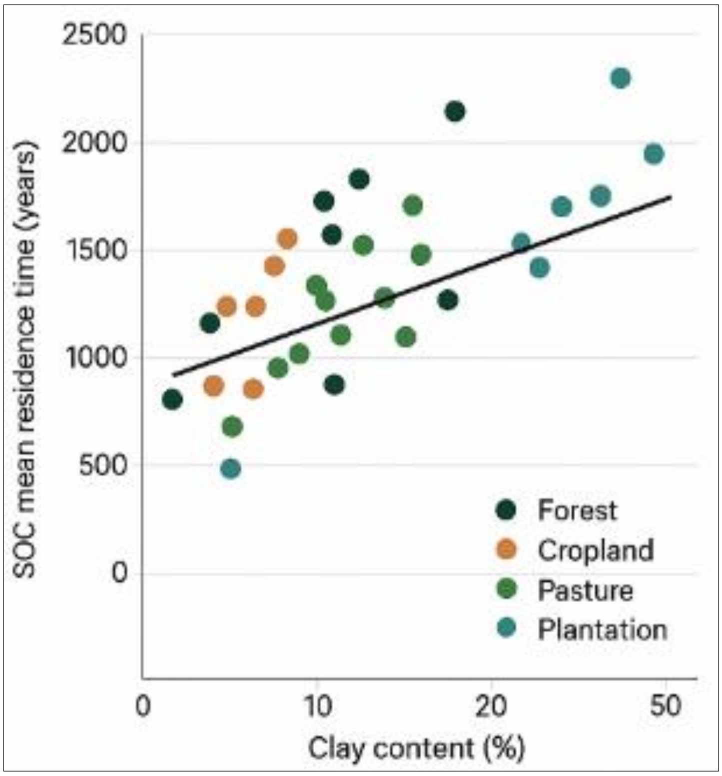
Table 1: SOC Stocks and Stability Metrics Across Land-Use Transitions

Land-Use Transition	SOC Stock Change (%)	Labile SOC (%)	Recalcitrant SOC (%)	Mean Residence Time (years)
Forest to Cropland	-30±5 [13]	-40±8 [14]	-15±4 [16]	10±2 [18]
Grassland to Cropland	-20±4 [14]	-35±7 [14]	-10±3 [16]	12±3 [18]
Cropland to Forest	+15±3 [15]	+20±5 [17]	+30±6 [17]	25±5 [18]
Grassland to Urban	-25±6 [20]	-50±10 [20]	-12±3 [16]	8±2 [18]



Caption: Bar chart showing percentage changes in labile (DPM) and recalcitrant (HUM) SOC pools after 10 years of land-use transition. Error bars represent standard deviation.

Fig 1: Changes in Labile and Recalcitrant SOC Pools Across Land-Use Transitions



Caption: Scatter plot of SOC mean residence time (years) versus clay content (%) across land-use types. Trendline indicates positive correlation ($R^2 = 0.65$).

Fig 2: Relationship Between Soil Texture and SOC Stability

Discussion

The results highlight the vulnerability of SOC to land-use transitions, particularly conversions to intensive agriculture. Tillage disrupts soil aggregates, exposing protected SOC to microbial decomposition [22]. This is evident in the rapid loss of labile SOC in croplands, which reduces soil fertility and carbon storage capacity [23]. Conversely, reforestation promotes SOC stability by increasing inputs of recalcitrant carbon and reducing physical disturbance [24]. These findings align with global studies showing that land management practices significantly influence SOC dynamics [25].

Management Implications

To enhance SOC stability, conservation practices such as reduced tillage, cover cropping, and organic amendments are critical [21]. For example, cover crops increased SOC stocks by 10% in croplands by enhancing root biomass inputs [26]. In urban transitions, green infrastructure (e.g., urban forests) can mitigate SOC loss by maintaining vegetative cover [20]. Policy incentives for sustainable land management, such as carbon credits, could further support SOC preservation [27].

Research Gaps

Despite advances, uncertainties remain regarding long-term SOC stability in urban systems and under climate change scenarios. Few studies address SOC dynamics in arid regions, where water availability limits decomposition [28]. Additionally, the role of microbial community composition in SOC stability requires further investigation, as shifts in microbial activity may drive unexpected SOC losses.

Conclusion

Land-use transitions profoundly impact SOC stability, with agricultural conversions reducing SOC stocks and reforestation enhancing them. Soil texture, climate, and management practices are key determinants of SOC dynamics. To mitigate SOC loss, sustainable practices like reduced tillage and reforestation should be prioritized. Future research should focus on long-term SOC trends in urban and arid systems and the role of microbial communities. Maintaining SOC stability is essential for soil health, carbon sequestration, and climate change mitigation, underscoring the need for integrated land management strategies.

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