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Can C-budget of natural capital be restored through conservation agriculture in a tropical and subtropical environment?☆

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ABSTRACT

Conservation agriculture through no-till based on cropping systems with high biomass-C input, is a strategy to restoring the carbon (C) lost from natural capital by conversion to agricultural land. We hypothesize that cropping systems based on quantity, diversity and frequency of biomass-C input above soil C dynamic equilibrium level can recover the natural capital. The objectives of this study were to: i) assess the C-budget of land use change for two contrasting climatic environments, ii) estimate the C turnover time of the natural capital through no-till cropping systems, and iii) determine the C pathway since soil under native vegetation to no-till cropping systems. In a subtropical and tropical environment, three types of land use were used: a) undisturbed soil under native vegetation as the reference of pristine level; b) degraded soil through continuous tillage; and c) soil under continuous no-till cropping system with high biomass-C input. At the subtropical environment, the soil under continuous tillage caused loss of 25.4 Mg C ha^{-1} in the 0–40 cm layer over 29 years. Of this, 17 Mg C ha^{-1} was transferred into the 40–100 cm layers, resulting in the net negative C balance for 0–100 cm layer of 8.4 Mg C ha^{-1} with an environmental cost of USD 1968 ha^{-1}. The 0.59 Mg C ha^{-1} yr^{-1} sequestration rate by no-till cropping system promote the C turnover time (soil and vegetation) of 77 years. For tropical environment, the soil C losses reached 27.0 Mg C ha^{-1} in the 0–100 cm layer over 8 years, with the environmental cost of USD 6155 ha^{-1}, and the natural capital turnover time through C sequestration rate of 2.15 Mg C ha^{-1} yr^{-1} was 49 years. The results indicated that the particulate organic C and mineral associate organic C fractions are the indicators of losses and restoration of C and leading C pathway to recover natural capital through no-till cropping systems.

1. Introduction

The biggest challenge for the global agricultural sector in the coming years will be to scale up those production systems which have the capacity to produce large amounts of biomass-C (Lugo-Morin, 2021) with diversity and frequency to improve crop productivity, mitigate climate

Abbreviations: list: NT, no-till; SNV, soil under native vegetation; SCT, soil under continuous tillage; NTCS, No-till cropping systems; SOC, soil organic carbon; POC, particulate organic carbon; MAOC, mineral associate organic carbon.

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change, and restore natural capital. The natural capital is an asset that supports a flow of benefits to society and encompasses all-natural resources (i.e., soil, water, air, biodiversity) and represents all the C accumulated in vegetation, organisms and soil serving the basis for ecosystems to produce food, fiber, wood, energy and the ecosystem services (Mace, 2019; Manning et al., 2018). The natural capital is one of the pillars in which the national or regional economy is based, and its depletion can limit economic growth, through global challenges of food insecurity, population growth, finite agricultural land, and abrupt climate change (Lal, 2015, 2019; Smith et al., 2016; Wackernagel and Rees, 1997).

Soil, being the foundation of natural resources and the key component for food security, is also critical to environmental sustainability (Amelung et al., 2020; Lal, 2014). Soil can be defined as an "organic C-mediated realm in which solid, liquid, gaseous and biological components interact from nanometer to landscape scale to make production and ecosystem services essential for all terrestrial life" (Lal, 2014). Soil is the main capital component of agricultural, livestock, forestry, environmental services production, and is also essential natural capital whose value depends on its status of use or degradation (Lal et al., 2020).

The soil organic C (SOC) content directly or indirectly controls the chemical, physical and biological attributes and is the main indicator for soil health and productive capacity (Sá et al., 2009) and must be considered in the valuation of natural capital (Crossman and Bryan, 2009). The soil C balance in terrestrial ecosystems can be expressed as follows:

$$\text{Soil Organic C} = \text{Photosynthesis C}\textit{input} - [(\text{Plants respiration C} + \text{Soil respiration C}) + (\text{Erosion C losses} + \text{leached C})]\ \textit{output}$$

where the Photosynthesis C input represents the primary net input through vegetation biomass (above and belowground from living plants or crop residues) and the other components constitute the transformations and C output. Thus, C accumulation in soil will occur only when the biomass-C input is greater than the C losses by erosion, decomposition and leaching (Lal, 2004; Lal et al., 2018; Sá et al., 2015). The challenge will be to manage the biomass-C input in order to exceed the minimum amount of C to achieve the C dynamic equilibrium level in the soil. For tropical environment, the minimum amount of C input is estimated at 5.1–5.8 Mg C $ha^{-1}yr^{-1}$ (Sá et al., 2015), while for the subtropical environment C input ranges between 3.2 and 4.0 Mg C $ha^{-1}yr^{-1}$ (De Oliveira Ferreira et al., 2021a; De Oliveira Ferreira et al., 2021b; De Oliveira Ferreira et al., 2012; Sá et al., 2014).

The SOC accumulation and the C restoration of partial or total natural capital is closely associated with the inherent capacity of each soil type to accumulate C. This means that C storage in the soil is finite, however the C stock at any given time may not reflect the level where C saturation occurs (Briedis et al., 2016; Briedis et al., 2018). The difference between the C saturation point and the current C stock can generate the C deficit (Briedis et al., 2018). Therefore, the capacity of the cropping systems to intensify the annual input of biomass-C is a strategic way to restore C (Briedis et al., 2016; Briedis et al., 2018; De Oliveira Ferreira et al., 2016; De Oliveira Ferreira et al., 2021a; De Oliveira Ferreira et al., 2018a; De Oliveira Ferreira et al., 2021b; Sá et al., 2015; Sá et al., 2014). The level and the turnover time of C recovery depends on the biome through its attributes comprising of climate characteristics, altitude, land scape position, parent material, soil texture, soil disturbance and the intensity of crop rotation (Amundson and Biardeau, 2018; Briedis et al., 2021; Briedis et al., 2018; Paustian et al., 2016; Smith et al., 2016).

Some questions to be addressed for advancing this scenario include: 1) Does it feasible to recover the C lost from deforestation and accumulate in the soil profile?, 2) What would be the paths that define the C recoverability and turnover time?, and 3) How big would the environmental impact be minimized through no-till cropping systems based on the high biomass-C input? Therefore, this study is based on the hypothesis that no-till based cropping systems with permanent soil cover, crop diversification and the addition of amount of biomass above the C dynamic equilibrium level can create positive C balance in soil and recover the C stock either partially or totally to the level of the native vegetation.

Thus, the objective of the present study was to evaluate the natural capital based on: i) soil under native vegetation (SNV), as the reference of an undisturbed soil and ecosystem representing the non-anthropized soil at the steady-state SOC level of natural capital, ii) soil under continuous tillage (SCT) with degraded and soil C-depleted, iii) continuous no-till cropping systems (NTCS) soil with C-restored and representing the conservation agriculture, and iv) the capacity of NTCS (based on the three principles of conservation agriculture) through intensive cropping systems via C enhancement restoring natural capital and the environmental value through the monetization of each incremental increase of Mg C ha^{-1} using the land market price.

2. Material and methods

2.1. Rationale of the natural capital

In this study, natural capital will be addressed as an asset that comprises total C contents in vegetation (above and belowground plus litter) and soil of 0–100 cm layer. The C content acts as the key component for soil functioning (see supplementary Figure 1), because it directly or indirectly controls physical (i.e., aggregation, porosity, density, water infiltration and resistance to root penetration), chemical (i.e., CEC, nutrient cycling, buffering power and redox potential) and biological attributes (i.e., C and N in the microbial biomass, microbiota diversity, decomposition rate, mineralization and nitrification). The integration of soil attributes improves soil quality and increases agronomic productivity of the system.

The native vegetation of the natural capital in the subtropical environment, is characterized by gallery forest, with tree species from less than 10 families whose trunk diameter at breast height varies from 10 to 40 cm. The mean annual precipitation is 1545 mm, without dry period and well distributed throughout the year, and the mean annual temperature is 18.5 Celsius degrees.

In the tropical environment, the natural capital vegetation consists of tree species from more than 10 families, whose trunk diameter at breast height varies from 10 to 70 cm and the tallest trees reach more than 10–15 m height. The mean annual precipitation is circa of 1950 mm with high incidence in the summer with dry period between April to September and the mean annual temperature is 25.7 Celsius degrees.

In addition, the economic valuation of C would allow a greater understanding of the contribution that soil conservation management have on the natural capital. Tol (2009) reviewed the literature on the social marginal damage cost of C, and observed that the average value is about USD $50 per Mg C as the upper bound, with an average of USD $43 per Mg C. In this study, the monetization of natural capital by C is based on the current land sale value through market price according to the economic potential of land use for agricultural purposes for each site. The criteria for assigning the land sale value comprised the following points: land with soybean production potential equivalent to 3.6 ton ha^{-1} and corn at 9.5 ton ha^{-1} with all the necessary infrastructure for grain production and storage. It is equivalent to the value of the land in its natural state (virgin soil and under native vegetation) in each climatic region and expressed in USD per Mg C ha^{-1}. The land value for each site is as follow: i) US$ 13,000 ha^{-1} for the Ponta Grossa-PR (PG site) at subtropical environment; and ii) US$ 12,000 ha^{-1} for the Lucas do Rio Verde-GO (LRV site) tropical environment.

The calculation of C value based on LRV site market price is described in an example below (Equation (1)):

Average market price for 1 ha of productivity land = US$12,000.

C stock in native vegetation (Aboveground, roots plus litter) = 95.6 Mg ha^{-1}

SOC stock at 0–100 cm layer = 130 Mg ha^{-1}

Total C stock (Native Vegetation + Soil) = 226 Mg ha^{-1}

$$C\ value\ at\ \text{natural capital} = US\$\ 12,000\ ha^{-1}/226\ Mg\ C\ ha^{-1} = US\$\ 53.10\ per\ Mg\ C\ ha^{-1} \quad (1)$$

where, US$ 12,000 refers to the land market value for 1 ha and 226 Mg C ha^{-1} refers to the total C stock including soil at 0–100 cm and vegetation (aboveground + roots at 1 m deep + litter).

The C balance was computed by using Equation (2):

$$C\ balance\left(Mg\ ha^{-1}\right) = SOC\ restored\ by\ NTCS - C\ losses \quad (2)$$

where, SOC restored means the C accumulated in the soil at 0–100 cm layer due to the NTCS compared to that under SCT, and the C losses refer to the C lost through deforestation of native vegetation by slash and burn to agricultural land plus the effects of continuous use of SCT. The market price for this study of each Mg C ha^{-1} is US$ 41.7 and 53.1 for PG (subtropical) and LRV (tropical environment) site, respectively.

2.2. Sites location, experimental design and description

The present study is based on a set of two tillage experiments conducted at subtropical and tropical climate of Brazil (Fig. 1). The first experiment represents the subtropical environment in southern Brazil at Ponta Grossa city herein called PG site, located at Paraná State, and the second experiment represents the humid tropical environment in Central Brazil at Lucas do Rio Verde city herein called LRV site, located at Mato Grosso State. The details of location, characteristics related to soil and climate, and experimental details of these two sites are presented in Supplementary Table 1 and in Sá et al. (2015).

The experiments comprised of two types of tillage systems: (i) soil under continuous conventional tillage (SCT), including disc plowing to 18- to 20-cm depth, followed by two narrow disking, and (ii) soil under continuous no-till cropping systems (NTCS), according to the principles of the conservation agriculture, which consists of no soil plowing (any disturbance restricted to the seeding row), permanent soil cover, and diversification of crop rotation. Both set of experiments were sited next to one another and comprising of an undisturbed soil under native vegetation for a reference of non-anthropized land use that represents the Natural Capital. At subtropical (PG site) and tropical (LRV site) region, treatments were established as whole plots, which were divided into six and three sub-plots at PG site and LRV site, respectively, for the purpose of soil sampling.

At the subtropical environment (PG site), the cropping sequence for management systems comprised of two annual crops (summer and winter). At the tropical environment (LRV site), the cropping sequence differed between tillage systems (see Supplementary Table 2). For the experiments, lime, fertilizer use, and farming operations were performed according to the technical recommendations, and these were identical for each tillage system.

2.3. Soil sampling and biomass-C input estimation

Soil samples to 1-m depth were obtained after 29 and 8 years of experimentation at the PG (Subtropical) and LRV (Tropical) sites, respectively. Soil bulk samples (disturbed soil) for depth intervals of 0–5, 5–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm was collected at four random points per plot, and composited. Soil bulk density (undisturbed soil) was determined by the core method (Blake and Hartge, 1986), and cores were obtained by using steel cylinders of known volume (5 cm in height and diameter) in the middle of each depth. At each site, soil samples were also obtained for the same depth intervals from an area under native vegetation in close proximity to the experiment (Fig. 1) to determine the baseline SOC and vegetation C stock. Inputs of above-and-belowground C under crops were calculated by using the harvest index (HI), the root to shoot (RS) ratio and the C concentration in biomass of each crop (Supplementary Table 2).

Estimates of the aboveground, belowground and litter biomass under native vegetation were made on the basis of the site measurements. Six benchmark measuring 30 × 50 m were marked to estimate the biomass. In each benchmark the trees were classified by their trunk diameter at chest level, as follows: < 30 cm; 30 to 50, 50 to 75 and > 75 cm in diameter. All trees were counted, classified and measured the total height. The biomass estimation of areas under native vegetation was

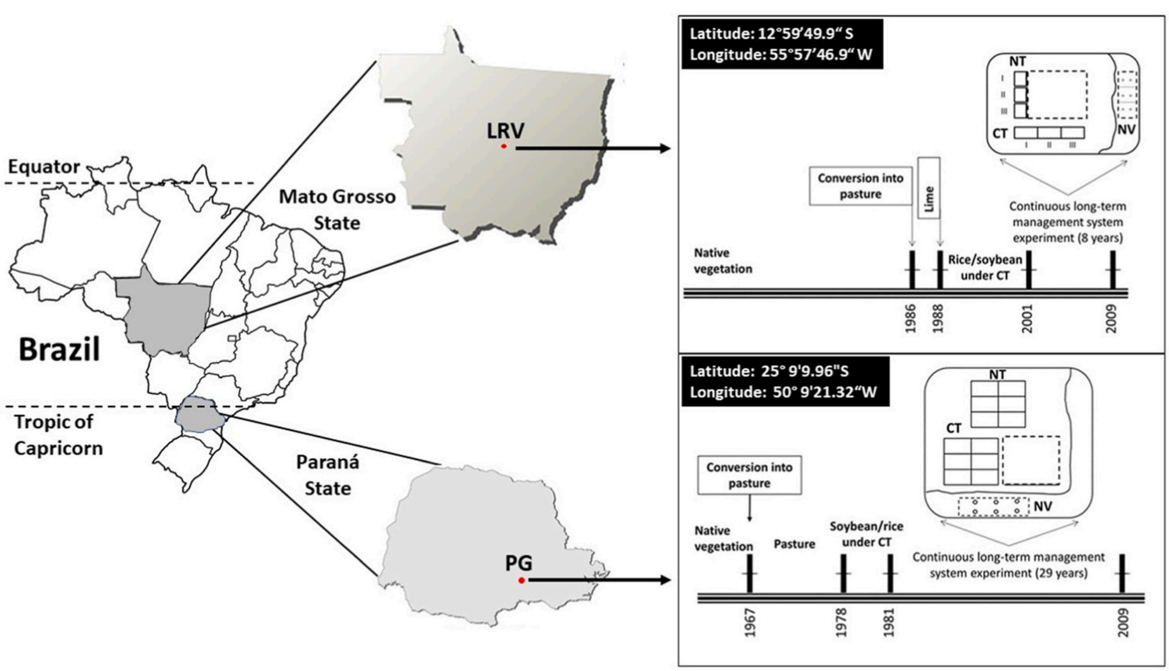

Fig. 1. Location and chronology of experimental sites in tropical and subtropical environment of Brazil.

through the use of regression equations based on attributes of tree species. The equation described by Brown et al. (1989) and ratified by De Castro and Kauffman (1998) is described in the supplementary information at biomass estimation. The amount of litter, branch fragments and debris were measured by 1 × 1 m frame at six points of each benchmark. We collected all organic material and was dried in an oven at 64 Celsius degrees, weighed and subsequently determined the C by dry combustion method (CN elemental analyzer - TruSpec CN, LECO, St Joseph, MI, USA).

2.4. Soil fractionation, carbon analyses and calculations

Soil fractionation (Supplementary Figure 3) was done following a process described by Briedis et al. (2018) and with detailed description in Supplementary Information. Briefly, the first fractionation step involved a partial dispersion and physical sieving of the soil (<2 mm) to obtain three size fractions: i) coarse particulate organic carbon (250–2000 μm, cPOC), ii) microaggregate fraction (53–250 μm, μAgg), and iii) easily dispersed mineral-associated organic C, (<53 μm, dMAOC). The second step involved a density fractionation of the μAgg fraction (obtained in the first step) to obtain the light POC (LPOC) fraction and a heavy fraction (HPOC), which was fully dispersed and sieved to obtain two fractions: i) intra-microaggregate POC (>53 μm, iPOC), and ii) MAOC derived from microaggregates (<53 μm, μMAOC). The third and last step involved an acid hydrolysis of the dMAOC and μMAOC fractions (obtained in the previous steps) to obtain non-hydrolysable (i.e., NH-dMAOC and NH-MAOC) and hydrolysable fractions of C (i.e., H-dMAOC and H-μMAOC). For realizing the objectives of this study, we merged some fractions and considered the hydrolysable (i.e., H-dMAOC and H-μMAOC) and non-hydrolysable (i.e., NH-dMAOC and NH-MAOC) as MAOC fraction and all particulate C fractions (i.e., cPOC, LPOC and iPOC) as POC.

The total organic C content of bulk soils and fractions herein is called soil organic carbon (SOC) was determined for the finely ground samples (<150 μm) by the dry combustion method using a CN elemental analyzer (TruSpec CN, LECO, St Joseph, MI, USA). The soil type of this study (Red Latosol, equivalent to Oxisol, FAO soil classification 2008) has less than 0.2% of inorganic C (Sá et al., 2014). The C stocks of bulk soils and fractions were calculated on equivalent soil mass–depth basis (Ellert and Bettany, 1995), where soil under NV was used as reference.

2.5. C saturation and C deficit stock

Soil C saturation stock was estimated based on the fraction silt + clay and represents the mineral associated organic C (MAOC) that best represented the asymptotic model. The equation used for C saturation level was: C fraction = $M\,(1 - e^{-kCBulk})$ where, M is the maximum C accumulation capacity (saturation level) of each fraction (g kg−1) and k is a first order rate constant (Briedis et al., 2018). The calculation was made for MAOC measured at each sampled layer and the sum of all layers represents the saturation potential for the 0–100 cm layer. The deficit of soil C stock was calculated by subtracting the current soil C stock from the C stock at the saturation level estimated by the asymptotic model as follow: Soil C stock deficit = SOC stock at saturation level – SOC stock at current level.

2.6. Calculations descriptions and equations

1) C losses (Mg ha^{-1}): represents the SOC losses due to conversion of native vegetation to agriculture and soil under continuous tillage use according the following expression:

$$\text{SCT C stock} - \text{SNV C stock}, \tag{3}$$

where, SCT C stock refers the soil C stock under continuous tillage and SNV is soil under native vegetation;

2) SOC recovered by NTCS (Mg C ha^{-1}): It refers to the amount of soil organic C stock recovered through NTCS according the following expression:

$$\text{NTCS C stock} - \text{SCT C stock}. \tag{4}$$

3) Conversion rate of Biomass-C into SOC by NTCS **(%):** It refers to the percentage of C from biomass (crop residues) converted to organic C in the soil.

4)

$$\text{Conversion rate} = \text{Total biomass} - \text{C input}/\text{SOC stock restored by NTCS}, \tag{5}$$

where the total biomass-C input refers the sum of all crop residues input during the experimental period, and SOC stock restored by NTCS is the amount of soil C accumulated by NTCS at 0–100 cm layer.

5)

$$\text{C balance}: \ \text{C Recovered by NTCS} - \text{C Losses}\ \left(\text{Mg ha}^{-1}\right), \tag{6}$$

6) Soil C sequestration rate; refers the C sequestration rate calculated as a function of the accumulated C stock and the experiment time.

$$\text{SOC sequestration by NTCS}\ \left(\text{Mg C ha}^{-1}\ \text{yr}^{-1}\right) = \text{C stock Recovered by NTCS}/\text{Years of experiment}, \tag{7}$$

7)

$$\text{Turnover time by NTCS (years)} = \text{C stock at balance level}/\text{C Sequestration Rate} \tag{8}$$

where soil C stock at balance it is expressed in Mg C ha^{-1} and soil C sequestration rates is expressed in Mg C ha^{-1} yr^{-1}.

8)

$$\text{Soil C saturation}: \ \text{C fraction} = M\left(1 - e^{-kCBulk}\right) \tag{9}$$

9)

$$\text{Soil C deficit} = \text{SOC stock saturation level} - \text{SOC stock current level}, \tag{10}$$

10) Total emissions by conversion of the natural vegetation + soil (0–100 cm layer) was calculated by multiplying the accumulated C loss from vegetation + soil, by the factor of 3.67, which represents C converted to CO_2e.

2.7. Statistical analyses

Differences among treatments for SOC stock were tested through analysis of variance (ANOVA). Mean values were compared using the Least Significant Differences (LSD) at the 5% probability level (Webster, 2007). Analysis was performed by soil depth, and results were considered statistically significant at $P < 0.05$. All statistical calculations were carried out using R software (R Core Team, 2012), package *aov*. SigmaPlot 12.0 was used for graphic representation. Regression analyses were carried out to assess the relationship in the impact of annual C-input on C-sequestered.

Table 1
C stock in the native vegetation, in the undisturbed soil under native vegetation (SNV) and the total biomass-C input by No-till cropping systems (NTCS) during the experiment period assessed.

Climatic zone	C stock in Native Vegetation				SNV C Stock	Total Biomass-C
	Aboveground	Roots	Litter	Total	(0–100 cm)	Input by NTCS[a]
	Mg C ha^{-1}				Mg C ha^{-1}	
Subtropical[b]	34.8 ± 2.8[§]	15.9 ± 1.7	3.6 ± 0.3	54.3 ± 4.9	258 ± 17	116 ± 9.3
Tropical	69.0 ± 6.2	15.2 ± 2.1	11.4 ± 1.2	95.6 ± 7.2	130 ± 12	67 ± 5.7

[a] Cumulative Biomass-C: refers the amount of biomass-C added during the experiment period assessed.
[b] Subtropical climate refers the location of Ponta Grossa - PG site, and Tropical refers Lucas do Rio Verde - LRV site; [§]Refers the standard deviation.

3. Results

3.1. Total C stock and C losses from native vegetation and soil upon conversion to agricultural land and continuous tillage

The total C stock (vegetation + soil) for the two studied sites showed a contrasting pattern. The C stock under native vegetation (Table 1) was higher in the tropical climate (LRV site) than those under subtropical altitude climate (PG site). In contrast, the soil C stock for the subtropical (PG site) was almost twice as high as that for LRV site in the tropics, (Table 1).

The C losses from burning the vegetation among subtropical (PG site) and tropical (LRV site) climate (Table 1) ranged from 54.3 to 95.6 Mg ha^{-1}, and those from the soil (0–100 cm layer) by continuous tillage ranged from 8.4 to 27.0 Mg ha^{-1}. The magnitude of SOC losses was influenced by tillage intensity, temperature, rainfall distribution and clay content.

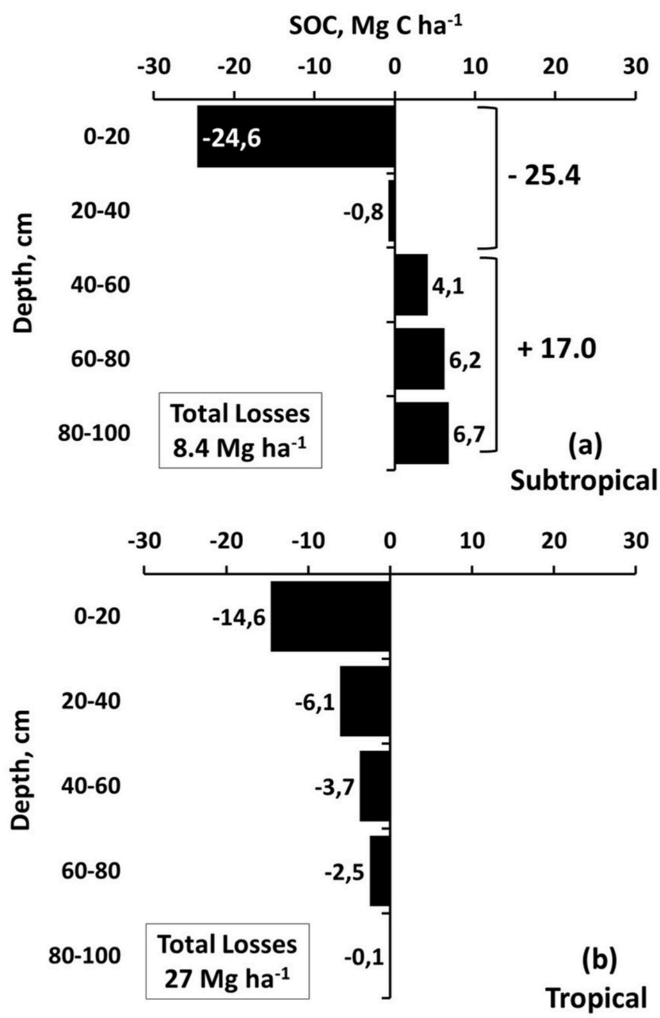

Fig. 2. Soil organic carbon (SOC) losses at 0–100 cm layer due continuous tillage: (a) subtropical environment (PG site), and (b) tropical environment (LRV site).

For the subtropical climate (PG site), the C lost from soil by continuous tillage was 25.4 Mg C ha^{-1}, and 97% (i.e., 24.6 Mg ha^{-1}) of it occurred from the top 0–20 cm layer (Fig. 2a). However, there was a gain of 17 Mg ha^{-1} into 40–100 cm layer, indicating C translocation from upper to the deeper layers (Fig. 2a), with the net negative C balance of 8.4 Mg ha^{-1} (Fig. 2a). Thus, the total C loss including that from the burning of native vegetation plus soil to 0–100 cm layer was 62.7 Mg ha^{-1} (Table 2). The economic environmental impact due to the C loss was US$ 2610 ha^{-1} (Table 3) for subtropical environment (PG site), and the total emissions upon conversion of native vegetation to agricultural land was 199.3 Mg CO_2e ha^{-1} over the 29 year period. Despite the loss and using 4.0 Mg C ha^{-1}yr^{-1} of biomass-C input, NTCS recovered 17.1 Mg C ha^{-1} over 29 years, at an average C sequestration rate of 0.59 Mg C ha^{-1} yr^{-1}. This recovery led to 100% of the SOC lost due continuous soil tillage and only 16.0% of the C from burning of native vegetation. However, the estimated turnover time of C loss from natural capital through NTCS can be over 77.3 year period.

For the tropical environment (LRV site), the total C stock (vegetation + soil) was estimated at 225.6 Mg ha^{-1} (Table 1). The burning of native vegetation during conversion to agriculture caused the loss of 95.6 Mg C ha^{-1} and the continuous soil tillage resulted in a loss of 27.0 Mg C ha^{-1} to 0–100 cm depth (Fig. 2b) over 8 years and equivalent to 20.8% of the total SOC. The SOC losses from 0 to 20 cm layer were 54.1% (i.e., 14.6 Mg C ha^{-1}), and the equivalent loss from the 20–100 cm layer was 45.9% (i.e., 12.4 Mg C ha^{-1}), indicating that losses from the deeper layers were similar to those from the surface layer (Fig. 2b). The production system over 8 years and adding 8.4 Mg C ha^{-1}yr^{-1} through NTCS recovered 17.2 Mg C ha^{-1} (Table 2). Therefore, the turnover time of C from natural capital based on 2.15 Mg C ha^{-1}yr^{-1} sequestration rate was estimated in 49 years.

The value of the economic loss of the environment due to conversion to agricultural land through continuous soil tillage was US$ 7065 ha^{-1} (Table 3), along with emissions of 386.8 Mg CO_2e ha^{-1} (vegetation + soil) over the 8 years period for the LRV site. On the other hand, the adoption of NTCS in subtropical climate with heavy clay soil recovered 100% of C lost by tillage and only 8.7% of that lost from burning of vegetation. Meanwhile, for the tropical climate (LRV site), NTCS recovered 66.9% of SOC and without any contribution to C recovery from burnt vegetation, indicating that the main strategy is to manage production systems which lead to a high input of biomass-C to reduce oxidation and enhance sequestration of soil C.

3.2. C deficit and saturation level in no-till cropping systems soil

In the subtropical environment (PG site) the current C stock under NTCS soil at MAOC fraction in the 0–100 cm layer is about 3 times lower than the stock at the saturation level (Table 4). The C saturation deficit in the 0–20 cm surface layer was 80.2 Mg C ha^{-1} while in the 20–100 cm layer increase for 426.3 Mg C ha^{-1} evidencing that as soil depth increases the C deficit increases reaching 507 ± 21 Mg C ha^{-1} (Table 4) in

Table 2
C-Budget of land use systems in a subtropical and tropical environment: C Losses through burning vegetation during conversion of native vegetation to agricultural land, C losses by continuous soil tillage, and C balance through no-till cropping system.

Subtropical[a]			Tropical		
C losses, Mg ha^{-1}					
Burning vegetation	Soil tillage[b]	Total	Burning vegetation	Soil tillage	Total
54.3 ± 4.9	8.4 ± 0.9	62.7	95.6 ± 7.2	27.0 ± 1.4	122.6
C balance, Mg ha^{-1}					
Annual C input[c]	C Sequestered[d]	C-Budget[e]	Annual C input[c]	C Sequestered	C-Budget
4.0 ± 0.4	17.1 ± 1.3	- 45.6	8.38 ± 0.8	17.2 ± 1.1	−105.4

[a] Subtropical: refers the PG site located at Paraná State in Atlantic Forest Biome, Tropical: refers the LRV site located at Mato Grosso State in Cerrado Biome.
[b] Refers the C losses by continuous tillage at 0–100 cm layer.
[c] Refers the annual biomass-C input through the cropping system for subtropical and tropical environment.
[d] Refers the SOC sequestration rate calculated through the total amount of C sequestered for the experimental period divided by number of years of the experiment.
[e] C-Budget: C Recovered by NTCS – Total C Losses (burning vegetation + soil tillage).

Table 3
Economic value of C from Natural Capital (soil and vegetation), C losses from Natural Capital (soil and Vegetation) by deforestation and plow-based tillage, and soil organic C (SOC) sequestered value by no-till cropping system (NTCS) and economic C balance in subtropical (Atlantic Forest, PG site) and tropical (Cerrado, LRV site) environment.

Environment	C Economic value[a]		C Losses by deforestation and tillage [b]			C Sequestered by NTCS and C balance [c]	
	Soil	Vegetation	Soil	Vegetation	Total	SOC Sequestered	C Balance
	USD ha^{-1}						
Subtropical	10740	2260	350	2260	2610	712	−1898
Tropical	7491	5509	1556	5509	7065	910	−6155

[a] Refers to the economic value of C in Natural Capital for 01 ha: Atlantic Forest (PG site = 13,000.00 USD/ha), Cerrado (LRV site = 12,000.00 USD/ha).
[b] Refers to the C losses of Natural Capital due deforestation (slash and burn of vegetation) and the continuous soil tillage for 01 ha, expressed in USD.
[c] C restoration by NTCS: SOC Sequestered, refers the amount of C accumulated at 0–100 cm layer through NTCS; and C Balance: refers the difference between SOC Sequestered by NTCS – Natural Capital C losses by SCT.

Table 4
Soil C stock at mineral associate organic C (MAOC) fraction in a no-till cropping systems land use in the current, saturation and deficit level for 0–100 cm layer in a subtropical (PG site) and tropical (LRV site) climatic regions.

Depth	Subtropical			Tropical		
(cm)	Current[a]	Saturation[b]	Deficit[c]	Current	Saturation	Deficit
	MAOC stock, Mg ha^{-1}					
0–5	24.1 ± 1.8	40.8 ± 1.9	16.7 ± 0.6	8.6 ± 0.6	15.2 ± 1.0	6.6 ± 1.5
5–10	19.6 ± 1.7	37.3 ± 1.8	17.7 ± 0.5	8.4 ± 1.7	16.0 ± 0.6	7.5 ± 1.1
10–20	30.2 ± 0.4	76.0 ± 2.3	45.8 ± 2.2	16.7 ± 3.4	34.2 ± 0.5	17.5 ± 3.9
20–40	52.0 ± 2.2	147 ± 6.7	94.6 ± 5.8	23.2 ± 2.1	69.1 ± 1.8	45.9 ± 1.0
40–60	46.7 ± 5.1	155 ± 13	109 ± 8.6	16.0 ± 0.4	66.3 ± 2.9	50.3 ± 3.2
60–80	41.0 ± 4.3	151 ± 15	110 ± 12	12.6 ± 1.1	64.9 ± 1.5	52.4 ± 0.8
80–100	38.1 ± 5.1	151 ± 8.6	113 ± 5.3	12.2 ± 1.4	68.8 ± 2.7	56.6 ± 1.5
0–100	252 ± 13	758 ± 24	507 ± 21	97.7 ± 9.0	335 ± 3.4	237 ± 11

[a] Current, refers the soil organic C stock of MAOC (mineral associate organic C) represented by Silt + Clay fractions measured for each layer sampled at no-till cropping systems land use change.
[b] C stock at Saturation point, refers the C stock value estimated by an exponential equation rise to maximum model (asymptotic) that representing C saturation behavior for silt + clay fractions using the equation: [C fraction = M(1-$e^{-kCbulk}$)] by Briedis et al. (2018) Catena, 163:13–23 (page 18, equation (4)).
[c] Deficit of C stock: calculated between the difference of the C stock at the saturation level and the current C stock. The signals (±) followed numbers refers the standard deviation of C current, C saturation and C deficit stock.

the whole soil profile (0–100 cm).

In the tropical environment the C deficit was even greater than in the subtropical environment, reaching 3.4 times the current stock for 0–100 cm profile. However, in the 0–20 cm layer the C deficit was 1.94 times reaching 65.3 Mg C ha^{-1} while in the 20–100 cm layer it reached 4.2 times accounting 269 Mg C ha^{-1} (Table 4).

3.3. The soil organic carbon fractions pathway from soil under native vegetation until its recovery through no-till cropping systems

The greatest C losses occurred through depletion of the POC fraction for both, subtropical and tropical climates, which amounted to 11.5 and 19.0 Mg C ha^{-1} (Fig. 3b and 3e) representing 60.5% and 43.2% of the POC stock in native vegetation soil-, respectively. However, a contrasting pattern occurred for the MAOC. There occurred an increase of 3.0 Mg C ha^{-1} in the subtropical environment (PG site) compared with a decrease of 8.0 Mg C ha^{-1} for the tropical environment (LRV site) and representing 9.3% of MAOC stock in native vegetation soil (Fig. 3b and e).

The recovery scenario followed two distinct paths: a) there occurred a significant increase in POC and MAOC for the subtropical environment under NTCS; b) for the tropical environment (LRV site) MAOC fractions increased and had a positive balance with the NTCS, except for the POC which was not fully recovered even with the high inputs of biomass-C. Over 29 years, the NTCS recovered 7.4 Mg C ha^{-1} (Fig. 3c) lost due to continuous soil tillage representing 39% of the POC stock in native

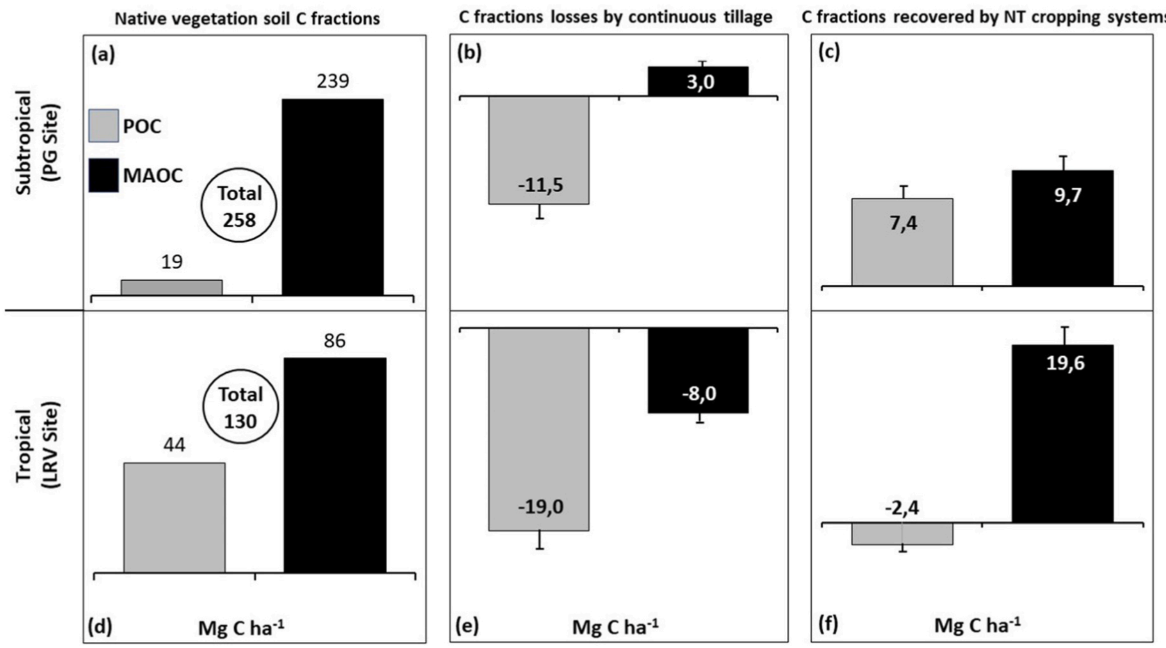

Fig. 3. (3a and 3d) refers the soil organic carbon (SOC) stock in particulate organic C (POC) and in mineral associate organic C (MAOC) expressed in Mg C ha^{-1} for 0–100 cm layer under native vegetation. Value inside circle represents the sum of the POC and MAOC fractions; (3b and 3e) POC and MAOC stock losses due continuous tillage in 0–100 cm layer; (3c and 3f) POC and MAOC stock fractions recovered through NTCS for 0–100 cm layer.

vegetation soil. There also occurred translocation of a part of POC into MAOC, since there was a significant increase in MAOC. At the tropical environment (LRV site), the NTCS recovered partially POC all the C lost in the MAOC fraction with an increase of 19.6 Mg C ha^{-1} (Fig. 3f).

4. Discussion

4.1. C-budget and turnover time perspective

The recovery of C lost from natural capital is closely related to the strategy of C input via biomass (i.e., above and belowground of crop residues) through adoption of innovative production systems. In the subtropical environment where winter has lower temperatures and frequent frosts, soil C decomposition rates are several times lower than those for the tropical environment (Bayer et al., 2006; Sá et al., 2015; Sá et al., 2014; Sá et al., 2006). In this study, the annual rate of C loss due to intensive soil tillage (for 0–100 cm layer) for the subtropical altitude environment (PG site) was 0.29 Mg C ha^{-1} yr^{-1}, and being circa 10 times lower than that in the tropical environment (LRV site) which was as high as 3.0 Mg C ha^{-1} yr^{-1}. Based on the SOC losses from 0 to 20 cm layer (Fig. 2a), the rate of C loss for the subtropical environment - PG site was almost three times lower (0.85 Mg C ha^{-1} yr^{-1}) than 1.83 Mg ha^{-1} yr^{-1} observed for the tropical environment - LRV site (Fig. 2b). The magnitude of SOC losses was influenced by temperature, rainfall distribution, clay content and the tillage intensity.

The minimum amount of C to be added annually to maintain the dynamic equilibrium level for the PG (subtropical environment) site was estimated at 3.2 Mg ha^{-1}yr^{-1} (De Oliveira Ferreira et al., 2021b; De Oliveira Ferreira et al., 2012). The annual biomass-C input through NTCS in this study was of 4.0 Mg C ha^{-1} yr^{-1} representing 25% more C above the equilibrium level, with a 0.59 Mg C ha^{-1}yr^{-1} sequestration and offsetting the soil C losses. However, the SOC sequestration rate of this study is far from those of 1.30 (Sisti et al., 2004), 1.61 (Sá et al., 2014) and 1.95 Mg C ha^{-1}yr^{-1} (Diekow et al., 2005) reported for subtropical environment indicating that the production system can be improved to add more biomass-C and trigger the enhancement of C sequestration rate. At the subtropical - PG site, the rotations with maize and black oats (S/O – M/O – S/W – S/O + V – S) in which total biomass-C input was 116.1 Mg ha^{-1} over 29 years (annual biomass-C rate of 4.15 Mg ha^{-1}), resulted in a rapid POC recovery. Working at a location in close proximity to the PG site (De Oliveira Ferreira et al., 2018b), reported that the contribution of 5.9 Mg ha^{-1} yr^{-1} in sand clay Oxisol and 7 Mg ha^{-1} year^{-1} in a clayey Oxisol, resulted in a similar POC recovery observed in the present study. However, for tropical environment (LRV site), even the high annual C input of 8.4 Mg C ha^{-1}yr^{-1} (i.e., 18.6 Mg ha^{-1} yr^{-1} of crop residues), was not enough to recover the POC over the 8 year period. In the present study, we added 98.4% (18.6 Mg ha^{-1} year^{-1}) more crop residues than required to attain the steady-state and the POC fraction is the most sensible C fraction affected by soil management (Sá et al., 2014).

These results support the hypothesis that the formation of extra-large macroaggregates and the C protection within intra-macroaggregate may be the primary mechanisms to enhance stability of C soils. Therefore, by managing the quantity (amount), quality (diversity of crop residues) and annual frequency of addition (number of annual additions), the turnover time of C in soil can be shortened from 35 to 23 years. Thus, the intensification of biomass-C input leads to two distinct pathways to stabilization of soil C: a) protection of C within intra-macroaggregates and reducing its oxidation (Briedis et al., 2016; Briedis et al., 2018; De Oliveira Ferreira et al., 2018b; Tivet et al., 2013); b) maintenance of flow of labile C and N forms that stimulate transformation of these organic compounds into more stable levels and leading to formation of new macroaggregates (De Oliveira Ferreira et al., 2018b; Sá et al., 2014). At the LRV site, increase in the rate of decomposition tripled the rate of loss of SOC observed because of the distribution of rainfall throughout the summer combined with the high mean annual temperature and high soil fertility of this layer. At the subtropical PG site, however, greater C protection occurred within intra-aggregates due to the high clay content and lower annual average temperature. The rapid decomposition throughout the year due to the more uniform rainfall distribution at the PG (subtropical environment) site may have generated a greater amount of free labile C compounds, weakly adsorbed on dispersed clay and silt particles, and prone to translocation into the 40–100 cm layer with the percolating water. Indeed, the leaching caused by intense rainfall induced translocation of 11.0 Mg C ha^{-1} into the 40–100 cm depth (Fig. 2a).

Furthermore, the input of biomass-C is also not enough to offset the losses of C by decomposition and the erosional impact of intense rainfalls. Translocation of C into the subsoil may be due to the displacement of decomposable labile compounds (i.e., low molecular weight organic compounds) and C associated with dispersed clay particles in the surface layer (Bayer et al., 2000; Tivet et al., 2013). The inversion of layers by soil tillage and the downward percolation of water to the deeper layers of the soil profile carrying displaced clay particles attached with organic compounds is an important pathway (Tivet et al., 2013). The recovery of C occurs through the POC fraction (Briedis et al., 2018; De Oliveira Ferreira et al., 2018b) that acts as an indicator of changes in soil C stock. Furthermore, it is the pathway to enhance C fractions associated with minerals and has greater ability to accumulate C. Therefore, the management of the trinity (i.e., quantity, diversification and frequency of addition of biomass-C) is the main strategy to maximize the input of biomass-C input for enhanced sequestration of C in soil. Thus, the rate of C loss can be curtailed by reducing the rate of oxidation, and enhancing aggregation of dispersed particles into stable macroaggregates (De Oliveira Ferreira et al., 2018b) by increasing input of biomass-C into the system. Cover crops with a prolific and robust root systems plus POC could be a key component of the re-aggregation process because it tends to form macroaggregates (De Oliveira Ferreira et al., 2018b) that increase intra-aggregate protection of encapsulated C (Six et al., 2000). In addition, the soil surface covered with crop residues or a live cover crop will result in the protection of more labile forms of C among aggregates leading to be encapsulated with the minerals (Briedis et al., 2021; De Oliveira Ferreira et al., 2018b; Tivet et al., 2013). The C losses at LRV site in 40–100 cm layers of ~40% may have been caused by the upward movement of water (capillarity) from the sub-soil layers below 1 m, stimulating the oxidation of the C of the soil between 40 and 100 cm layers during the dry period. The bare soil without vegetation cover is prone to the upward flow that may cause emission of the labile and more volatile C compounds out of the soil profile. The proposed trinity may stabilize more labile forms of C over time, and increase the soil resilience (Sá et al., 2014). Formation of a stronger bond between C compounds with clay minerals over time would lead to creation of more humified organo-mineral complex and resilient macroaggregates with a longer half-life of C and more stable soil structure. Therefore, cropping systems based on input of biomass-C with quantity, quality and frequency will create a continuous C and N flow that stimulates the interactions among soil attributes (see Fig. 1, Supplemental information), increasing C translocation and restoring the natural capital.

4.2. Natural capital C balance

The conversion of native vegetation to agricultural land use had a strong environmental impact caused by the loss of 100% of C storage in the vegetation through the burning of biomass. The loss of biomass C represented an economic value of US$ 2260 and US$ 5509 ha^{-1} for subtropical (PG site) and tropical (LRV site) sites, respectively, and equivalent to 17.4% and 45.9% of the natural capital leading to a sharp decapitalization of equity (Costanza et al., 2014). The C losses due the continuous soil tillage, despite being proportionally smaller compared to those by the burning of vegetation, leads to severe changes in the physical, chemical, and biological attributes affecting soil functionality. The economic value of C losses in tropical environments was equivalent to 21% of the NC.

If we consider the economic investment made in the purchase of land and its improvement to achieve a high level of production, the loss of natural capital limits the return capacity of the economic capital invested.

The drastic loss of the terrestrial C stock can collapse soil functionality chain, which is set-in- motion by changing the interactions that occur between the SOC content and the attributes (physical, chemical and biological) that govern the capacity of the soil ecosystem to perform its functions (Sá et al., 2009). The trigger for recovering the NC is set-in-motion by the intensification of input of biomass-C creating productions systems that include cover crops with robust and abundant root system and aboveground biomass, providing a continuous soil cover and protecting stability of aggregates. The annual rate of C sequestration for the subtropical PG site at 0.59 Mg C ha^{-1}yr^{-1} based on 4.0 Mg C ha^{-1}yr^{-1} was little more than the minimum C required to attain the dynamic equilibrium level for that environment (i.e., 3.2 Mg C ha^{-1}yr^{-1}) (De Oliveira Ferreira et al., 2021b; De Oliveira Ferreira et al., 2012). However, the rate of soil C sequestration can be enhanced by 2.2–3.3 times higher such as cited by Sisti et al. (2004), Sá et al. (2015) and Diekow et al. (2005) and the turnover time of NC can be reduced to < 25 years. For the tropical environment, the minimum C required to attain the dynamic equilibrium level is 5.1 Mg ha^{-1}yr^{-1} (Sá et al., 2015) and the annual biomass-C input was 8.38 Mg C ha^{-1}yr^{-1} in which the C sequestration rate was 2.15 Mg C ha^{-1}yr^{-1}. Even the high current rate of C sequestration can be increased to 2.6 Mg C ha^{-1}yr^{-1} (Sá et al., 2006) by enhancing the production system with species mixing legumes and grasses (i.e., Crotalaria + Brachiaria or cajanus cajan + corn + brachiaria) that can add high amount of biomass-C into the system. The potential C stock would be 758 and 335 Mg C ha^{-1} for subtropical (PG site) and tropical (LRV sites), while the current stock are 252 and 91.7 Mg C ha^{-1} (Table 4), respectively. Thus, the C deficit would be 507 and 237 Mg C ha^{-1} (Table 4), equivalent to 15.8 and 13.4% in the first 0–20 cm layer and 84.2 and 86.6 in the 20–100 cm layer, respectively. This clearly indicates that not only we can store the C lost from native vegetation (54 and 95 Mg C ha^{-1}, for PG and LRV sites, respectively) during conversion to agricultural land, but also C from biomass additions by the long-term NTCS. The longevity of C in soil can be achieved by minimizing the SOC oxidation level and re-aggregating the dispersed clay and silt fractions to create new macro-aggregates by cementation and stabilization of micro-aggregates in soil (Tisdall and Oades, 1982).

In summary, the restoration of natural capital needs to reach the following premises: a) increasing the biomass-C input according to the three pillars that support a conservation agriculture system, adding the amount at the rate above that of the dynamic equilibrium, guaranteeing a controlled soil C oxidation rate, and promoting the continuous C and N flow to reorganize the aggregates and the new structure; b) stimulating macroaggregation and enhancing C protection within intra-aggregate and stabilizing it overtime and restoring soil functionality by improving soil's chemical, physical and biological attributes; and c) managing the rate of input of biomass-C as a key strategy to decrease C turnover time, and leading to the restoration of natural capital and ecosystem services to society.

5. Conclusions

The results of this study reinforce that the recovery of natural capital is accessible and feasible through the input of quantity, quality and frequency of the biomass-C through no-till cropping systems. The soil C loss was 3.2 times higher in the tropical than those in the subtropical environment. However, the soil C losses in the subtropical environment was higher in the top 0–20 cm layer (i.e., 97%, 24.6 Mg C ha^{-1}) while in the tropical environment the C losses occurred throughout the 0–100 cm layer (54.1% in 0–20 cm, and 49.9% in 20–100 cm layer. We also can conclude that the particulate organic C and the mineral associated organic C were strong indicators of the alterations caused by soil under continuous tillage and the no-till cropping systems in subtropical and tropical environments. The soil C saturation level in the silt + clay fraction was 3.0 and 3.4 times higher than those of current C stock (0–100 cm layer) for subtropical and tropical environment, respectively. The path to recover the C lost from native vegetation and soil passes through particulate organic C leading mineral associate organic C formation by the no-till cropping systems through high biomass-C input, decreasing the rate of oxidation and promoting a continuous C flow to offset the C losses. The turnover time based on the C sequestration rates in subtropical and tropical environment recovered the C lost from native vegetation + soil in 77 and 49 years, respectively, indicating that the key strategy to restore natural capital is to manage the sequestration rate of the production systems through biomass-C input.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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