Diachronic assessment
of soil organic C and N dynamics under long-term no-till
cropping systems in the tropical upland of Cambodia

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Abstract

No-till (NT) cropping systems have been proposed as a strategy to combat soil degradation by storing soil organic carbon (SOC) and total nitrogen (TN). ~~No-till (NT) cropping systems have been proposed as a potential strategy to combat soil degradation and global warming by storing soil organic carbon (SOC) and nitrogen (N). Yet, there are ongoing debates about the real benefits of NT systems and factors influencing SOC and N accumulation. Assessing the dynamics of SOC and N on the long-term is needed to fill knowledge gaps and provide robust scientific evidence for potential additional SOC storage.~~ We quantified the impacts of NT cropping systems on the changes in SOC and ~~-~~TN stocks ~~in bulk soil~~ and in particulate and mineral-associated organic matter fractions (POM and MAOM) ~~stocks and fractions~~, ~~down~~ to 100 cm depth, from three 13-year-old experiments in a tropical red Oxisol in Cambodia using diachronic and equivalent soil mass approaches.~~, comparing conventional tillage (CT) to NT monocropping and NT crop rotation systems using a diachronic and equivalent soil mass (ESM) approach.~~ Established in 2009 and arranged~~The three experiments~~ in a randomized complete block design with triplicates, the experiments included~~comprised~~ maize (MaiEx)~~-~~, soybean (SoyEx)~~-~~, and cassava (CasEx)-based cropping systems~~ experiments~~.~~trials, hereafter called MaiEx, SoyEx, and CasEx, respectively~~ Each experiment comprised three treatments: (1) monocropping of main crops (maize, soybean, and cassava) under conventional tillage (CTM); (2) ~~comparing with~~ monocropping of main crops under NT systems with the use of cover crops (NTM); and (3) bi-annual rotation of main crops under NT systems with the use of cover crops (NTR), both crops being presented every year and represented by NTR1 and NTR2. Soil samples were collected in 2021, 10 years after the ~~first~~ last sampling ~~(in 2011)~~.~~, at 7 depths: 0–5, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. Over~~

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~~the 10-year period (2011–2021), significant impacts on SOC stock and its vertical distribution differed among the NT systems and in the three experiments~~ All the NT systems significantly ($p < 0.05$) increased SOC stock in the topsoil ~~of the stock~~ in SoyEx and MaiEx and down to 40 cm in CasEx. C~~. In MaiEx and CasEx, the soils under all the NT systems significantly (P > 0.05) accumulated SOC stock across the soil depths, with the accumulation ranging from 6.97 to 14.71 Mg C ha~~$^{-1}$ ~~in the whole profile (0–100 cm). In SoyEx, significant increase in SOC stock was limited to the top 0–20 cm under NT monocropping, whereas NT crop rotation systems had significantly accumulating SOC stock from 0 to 80 cm depths. When c~~considering the whole profile (0–100 cm) ~~(0–100 cm)~~, the ~~as a single stratum, the annual~~ SOC stock ~~cumulative rate in NT systems~~SOC accumulation rates ranged~~ed~~ from 0.86–1.47~~, 0.65–1.00,~~ and 0.70–1.07 Mg C ha^{-1} yr^{-1} in MaiEx~~, SoyEx,~~ and CasEx, respectively. ~~In the top 0–10 cm, NT systems significantly increased C concentration in particulate organic matter (POM) by 115%, 118%, in MaiEx and SoyEx, respectively, and by 37% in CasEx a~~Although SOC stock significantly increased in CTM in 0–20 cm in MaiEx and CasEx, it remained stable in 0–100 cm in all the experiments. ~~not significantly. Similarly, at 0–10 cm depth, NT systems significantly enhanced C concentration in the mineral-associated organic matter (MAOM) by 33%, 21%, in MaiEx and SoyEx, respectively. Significant increase of C in MAOM was also observed from 0 to 40 cm in CasEx.~~ In 0–5 cm, ~~In contrast, total N stock in~~ NTR ~~system~~oils~~ cropping~~ systems significantly increased TN stock in all the experiments, ~~in the surface 0–5 cm depth but~~ while in NTM system it was only significant in MaiEx and SoyEx~~decreased below 10 cm and in the whole profile~~. In 0–100 cm, TN stock in all the experiments remained stable under NTR systems, whereas significant decrease was observed under NTM systems in SoyEx and CasEx. Although C~~(0–100 cm), particularly under The significant effects of NT monocropping with an annual loss rate of~~

~~-0.10 and -0.17 Mg N ha^{-1} yr^{-1} in SoyEx and CasEx, respectively. Although NT A significant increase systems increased N c~~i~~oncentrationSO in -~~POM stock significantly increased under all NT systems limited to 0– ~~in the top 0–10 cm of MaiEx and SoyEx, a decreasing trend was observed below 10 cm depth. The N concentration in POM under NT systems in CasEx also decreased with soil depth. From 2011 to 2021, N concentration in MAOM was foundunder NT systems remained stable in MaiEx and SoyEx in the top 0–~~10~~5~~ cm ~~in NT cropping systems, but significant decreases~~ in MaiEx and ~~CasEx~~ SoyEx, ~~the~~all the NT systems significantly increased~~in SO~~ C-MAOM stock in the 0–10 cm layer in MaiEx and SoyEx and ~~was found stock~~ down to 40~~below 5~~ cm ~~was detected~~ in CasEx. All the ~~In contrast to C pools,~~ NT systems ~~Tfractions~~significantly increased N-POM stock in 0–10 cm in MaiEx and SoyEx, while a significant decreased in N-MAOM stock was observed below 5 cm in CasEx and below 40 cm in MaiEx and SoyEx.

Our findings s~~uggest~~howed that ~~adopting~~ long-term NT ~~cropping~~ systems with ~~diverse~~ crop ~~and cover crop~~ species diversification ~~and high biomass C inputs in the long-term leads to SOC~~ accumulated SOC~~ion~~ not only ~~i~~on the surface but also in ~~d~~the~~eper~~ whole profile ~~layers,~~ by increasing both ~~the~~ SOC ~~pools~~ in the POM and MAOM ~~size fractions~~, even ~~on~~ in the cassava-based system.~~, which is believed to be an annual crop that could cause serious soil fertility depletion.~~ This study highlights the potential of NT ~~cropping~~ systems f~~t~~or storinge SOC over time~~,~~, but raises questions about soil N dynamics. ~~but raises questions about soil N dynamics.~~

1 Introduction

Land and soil degradation is a global challenge with consequences not only for food and nutrition security but also for livelihoods, environmental pollution, climate change, water scarcity, and biodiversity. The main processes that cause soil degradation are water and wind erosion, chemical depletion, physical deterioration, decline in soil organic carbon (SOC)~~ pools~~, loss in biodiversity, acidification, and salinity (Lal, 2015a; Stavi and Lal, 2015; Dragović and Vulević, 2020; Barbier and Di Falco, 2021). It was estimated that about 562 million ha of land are degraded worldwide, with 5 to 10 million ha of land lost each year as a result of severe degradation (Stavi and Lal, 2015; Nkonya et al., 2016). The major factors contributing to soil degradation are deforestation and land clearance, the overuse of agrochemicals, and in~~appropria~~tensive agricultural management practices (Dragović and Vulević, 2020). Tropical soils have the highest risks of degradation due to the combination of high rainfall intensity and the ongoing intensification of agriculture to meet the food demand of a fast-growing population, which is also constrained by the limited availability of land to be converted to cropland (Barbier and Hochard, 2018; Craswell and Lefroy, 2001; Barbier and Di Falco, 2021).

Cambodia, located in the tropical region of Southeast Asia, is one of the highest land degradation hotspots in the world, and about ~~60~~55% of the country's population reside in these hotspot areas (UNCCD, 2018). In the last two decades, human-induced activities including deforestation, land clearance for agriculture, climate change, and in~~appropria~~tensive farming practices have further worsened Cambodia's already poor soil fertility (UNCCD, 2018; Ken et al., 2020; ADB, 2021). Over the past two decades, 30%, or about 4.24 million ha, of forest areas were converted to croplands, putting pressure on natural resources, biodiversity, and threatening the provision of several ecosystem services (World Bank Group, 2023). In

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the Northwest rainfed uplands, like in other parts of the country, studies on soil erosion at field scale and modelling reported that the annual soil loss rate in conventional plough-based tillage (CT) ranged from 0.33 to more than 80 Mg soil ha^{-1} yr^{-1}, depending on soil type and land slope (CARDI, 2017; Nut et al., 2021; Sourn et al., 2022). The amplitude of soil erosion increased by 41% from an annual erosion rate of 2.92 Mg soil ha^{-1} yr^{-1} in 1998 at the beginning of the forest conversion to agriculture with extensive, more diversified farming practices to 4.98 Mg soil ha^{-1} yr^{-1} in 2018 under CT maize- and cassava-based monocropping systems (Nut et al., 2021; Sourn et al., 2022, 2023). It was estimated that approximately 3–4 mm of topsoil is washed away annually for this Northwestern region of Cambodia (Nut et al., 2021; Sourn et al., 2023). Erosion induces soil degradation and a ~~SOC~~ loss of SOC for the eroded fields (Polyakov and Lal, 2004). It was estimated that from 2000 to 2010, Cambodia lost approximately 1.98 million Mg C in the top 0–30 cm depth as the consequence of forest conversion to other land uses (MAFF, 2018). Cambodian soils are seriously threatened by ~~inappropriate~~intensive agricultural systems. The returns on taking actions against land degradation through restoration and adoption of sustainable agricultural management practices are estimated at 3 US dollars for every dollar invested in restoring degraded land in Cambodia, highlighting the strong economic benefits (UNCCD, 2018). ~~Therefore, taking actions to reverse the trend of soil degradation through restoration and adopting sustainable agricultural management practices highlights the strong economic benefits while combating soil degradation in the country (UNCCD, 2018).~~

SOC serves as the foundation of soil physical, chemical, and biological processes that sustain essential ecosystem functions, and it is the reservoir of plant nutrients and energy for biota (Lal, 2015a). Therefore, adopting sustainable management practices that lead to increase in SOC ~~content~~ stock (Beillouin et al.,

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2023) is part of the key strategies to reverse the soil degradation trends and to minimize the economics and environmental impacts related to land degradation (Lal, 2015a; Obalum et al., 2017). Studies reported that agricultural practices, in particularly those based on CT, weaken soil structure, accelerate soil erosion, and deplete SOC stock (Tivet et al., 2013; Sá et al., 2014; Briedis et al., 2018; Oliveira et al., 2020; Tiecher et al., 2020). By contrast, conservation agriculture (CA), defined by three key principles, (i) minimum or no soil disturbance, (ii) permanent soil cover with mulch or cover crops, and (iii) crop diversification through rotation or association, is a potential strategy to overcome soil degradation (Luo et al., 2010; Lal, 2015b; Powlson et al., 2016; Obalum et al., 2017). No-till cropping systems (NT), are part of the conservation agriculture practice approach, and involve a range of practices with a reduction or an absence in soil tillage and a high diversity of ~~plant~~ crop and cover crop species~~, amount and frequency of biomass-C inputs (e.g., main crops and cover crops)~~. The benefits of ~~CA and~~ NT cropping systems on soil health improvement have been reported worldwide. ~~Since 2004, the conservation agriculture research for development programs have been initiated by the joint-collaboration between the General Directorate of Agriculture (GDA) and Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France.~~ Diversified NT cropping systems enhance both ~~the~~ SOC stock ~~in the topsoil surface layer only after a several years of implementation~~ (Hok et al., 2015) and pools (Sá et al., 2014; Briedis et al., 2018; Sithole et al., 2019; Cooper et al., 2021; Rodrigues et al., 2022), especially through an increase in physical protection of ~~SOC~~particulate organic C (Sithole et al., 2019) and mineral-associated organic C ~~inside soil aggregates~~ (~~Six et al., 2002; Sithole et al., 2019;~~ Rodrigues et al., 2022) inside soil aggregates. In addition, numerous studies have reported the co-benefits of NT cropping systems on soil health enhancement (Pheap et al., 2019; Koun et al., 2023), increased water infiltration,

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reduced soil erosion (TerAvest et al., 2015; Sithole et al., 2019), ~~and~~ enhanced microbial activities (Hok et al., 2018) and abundance (Lienhard et al., 2013). Yet, there are still arguments about the benefits of ~~CA and~~ NT cropping systems and associated factors that determine SOC accumulation. Particulate organic matter (POM) and mineral-associated organic matter (MAOM) are the two main fractions of the SOC pools. They differ in physical and chemical characteristics as well as their turnover rates. POM is more sensitive to soil tillage and land use than MAOM and total SOC (Blanco-Moure et al., 2013; Kan et al., 2021). ~~In addi~~Therefore~~tion~~, documentation of SOC fractions is desirable for a better understanding of SOC dynamics and stabilization processes (Lavallee et al., 2020). In a meta-analysis with the majority of the studies collecting samples between 0.15 and 0.3 m depth, Powlson et al., (2016) reported that SOC accumulation rate under CA systems ranged from 0.16 to 0.49 Mg C ha^{-1} yr^{-1} in tropical soils in the Indo-Gangetic Plains and from 0.28 to 0.96 Mg C ha^{-1} yr^{-1} in Sub-Saharan Africa. In a Ferralsol in Zimbabwe, Shumba et al., (2024) reported a SOC accumulation rate of 0.13 Mg C ha^{-1} yr^{-1} in the 0–5 cm layer only under CA, but not change under NT only. However, in meta-analyses, Angers and Eriksen-Hamel (2008) and Luo et al., (2010) found that conversion from CT to NT only changed the SOC distribution in the soil profile but did not significantly increase SOC stock in the whole profile. Boddey et al., (2010) and Xiao et al., (2020) reported that NT significantly increased SOC stock only at the soil surface but not in the deeper layers. It is therefore crucial to quantify SOC change in subsoil when assessing the impact of practices, especially ~~in CA and~~ NT systems.

S~~oil organic~~ OC ~~sequestration~~storage is closely related to soil aggregate structure (Six et al., 2004; Liu et al., 2021). The complexity of cropping systems, characterized by crop species diversity through the use of cover crops, crop rotation, and intercropping, was reported to enhance soil aggregation stability and

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the proportion of soil macroaggregates, along with ~~the~~an increase ~~of~~in SOC (Tiemann et al., 2015; Li et al., 2024). The diversity of crop species increased the quantity and chemical diversity of plant-derived litter inputs, which are the main sources of energy for soil microorganisms, and increased microbial activity and the abundance of fungal and bacterial communities (Tiemann et al., 2015; Zhang et al., 2023). The overall increase in fungal hyphae, plant roots, and aboveground biomass inputs under crop diversification are important organic binding agents that promote the formation of macroaggregates and facilitate the soil aggregation process (Tiemann et al., 2015). Furthermore, the increased amount and diversity of plant-derived C inputs in the forms of crop residues and root exudates provided a suitable microenvironment for soil microorganisms, which promoted microbial growth and turnover (Morugán-Coronado, 2022). The faster microbial growth and turnover rates increased the amount of microbial biomass and necromass, thus increasing SOC (Liang et al., 2011; Prommer et al., 2019). The amount, quality and frequency of the crop residues added to soil under a range of climate-driven decomposition rates, soil mineralogy and profile characteristics are important factors to consider to increase SOC stocks (Paustian et al., 1997; Six et al., 2002; Bayer et al., 2006; Ogle et al., 2012; Virto et al., 2012). It has been suggested that the amount of biomass-C inputs was the main factor explaining the variability in SOC storage between sites under NT (Virto et al., 2012). In a synthesis from tropical soils, Fujisaki et al., (2018) reported that the amount of biomass-C inputs was the main factor driving ~~a positive C budget, enhancing C and N transformations, flow, and~~ SOC stock change. In a meta-analysis in Sub-Saharan Africa, Corbeels et al., (2019) found that ~~not disturbing the soil~~no-tillage alone does not lead to an increase in SOC stock, but CA systems combining the three principles could. It therefore seems that there is a hierarchy in CA principles to increase SOC stock, the most important one being the permanent soil cover,

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followed by a reduction in soil tillage and improved rotations (Shumba et al., 2024). This has been confirmed in a recent second-order meta-analysis where crop residue retention and cover crops were the most efficient CA practices to increase SOC (Beillouin et al., 2023).

~~In addition, u~~Using ~~improper methods could mislead the assessment of the long-term impact of management practices on the SOC stock. There are t~~Two different soil sampling approaches are commonly used for assessing SOC ~~accumulation rates:~~stock change, the diachronic and the synchronic approaches (Bernoux et al., 2005). The diachronic approach refers to collecting samples on the same field plots over time. The synchronic approach, also known as the space-for-time method, ~~on the other hand,~~ refers to sample collection at the same time from different (often adjacent) field plots under different land-use or management systems (Bernoux et al., 2005; Neto et al., 2010). Neto et al., (2010) and Junior et al., (2013) revealed that the synchronic approach led to ~~overestimated~~ bias~~s~~ed estimation of SOC accumulation from long-term experiments in Brazil due to spatial heterogeneity and initial land use history. They highlighted that diachronic soil sampling should be used for assessing soil SOC storage rates due to changes in land-use or management patterns because it offers a more comprehensive view of how SOC and N levels change under long-term tillage and cropping systems over time in which non-identical initial soil conditions cannot practically be excluded, making it more accurate and realistic for the investigation of SOC and N dynamics, despite the fact that they are costly and require significant time and resources (Bernoux et al., 2005; Neto et al., 2010; Junior et al., 2013). The synchronic approach, on the other hand, is simpler, lower-cost, and less time-consuming, but comes with more uncertainty ~~they may overlook the effects of NT systems over time since it is impossible to eliminate all environmental factors other than the impacts of NT systems that influence SOC and N content because of the high spatial~~

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~~variability of land use history prior to the conduct of the experiments~~ (Neto et al., 2010; Junior et al., 2013). A change in soil bulk density is often observed when comparing ~~CA and~~ NT systems to CT, due to differences in tillage but also to root systems of cover crops. It is therefore required to estimate SOC change using an equivalent soil mass approach instead of a fixed depth approach (Ellert and Bettany, 1995).

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~~Cambodian soils are seriously threatened by inappropriate agricultural systems. The returns on taking actions against land degradation are estimated at 3 US dollars for every dollar invested in restoring degraded land in Cambodia. Therefore, taking actions to reverse the trend of soil degradation through restoration and adopting sustainable agricultural management practices highlights the strong economic benefits while combating soil degradation in the country (UNCCD, 2018). Since 2004, the conservation agriculture research for development programs have been initiated by the joint-collaboration between the General Directorate of Agriculture (GDA) and Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France. CA and~~ NT cropping systems have been promoted to smallholders in various agroecosystems in ~~the country~~Cambodia since 2009. The early effects of NT cropping systems on soil health, and SOC ~~sequestration~~ storage have been reported in several studies (Hok et al., 2015, 2018, 2021; Pheap et al., 2019; Suong et al., 2019; Sar, 2021; Koun et al., 2023), however, the information on the impact of long-term NT systems on the changes in SOC and TN stocks remains~~s~~ scarce in the country as well as in Southeast Asia. There is a need to document the long-term changes in SOC and TN stocks under ~~CA and~~ NT cropping systems to fill in the knowledge gaps as well as provide robust evidences to land use planners and policymakers. This could be profitable not only for Cambodia but also for other countries in the ~~whole~~ region.

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Therefore, this study aimed to quantify the impacts of CT and different NT cropping systems on the changes in SOC and ~~total nitrogen (~~TN~~)~~ stocks and fractions over time (2011–2021) in Cambodia's tropical red Oxisol using diachronic and equivalent soil mass (ESM) approaches. We hypothesized that implementation of the three core technical principles of CA would significantly enhance the SOC stocks, both in the POM and MAOM size fractions, including in the subsoils~~ over time~~. ~~In addition, calculating SOC stock using the diachronic approach would prevent a biassed estimation of the SOC accumulation when compared to the synchronic approach.~~

2 Materials and Methods

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2.1 Study site description

The study was conducted at Bos Khnor Conservation Agriculture Research Station, the oldest CA research station in Southeast Asia, which belongs to the General Directorate of Agriculture (GDA), Department of Agricultural Land Resources Management (DALRM). It is located in Chamkar Leu district, Kampong Cham province (12°12'31.0"N 105°19'07.0"E, 118 m above sea level). The details of the study site were reported in Hok et al., (2015). Briefly, the site was the natural tropical rainforest, which was then converted to perennial cropland in 1937. The crops included cashew, coffee, mango, mulberry, avocado, and rubber, which were planted soon after forest clearance. Because of the civil war (Khmer Rouge) between 1970 and 1982, the area was abandoned and taken over by several tree species, such as *Tetrameles nudiflora* R Br., *Nauclea officinalis* L., *Cassia siamea* (Lam.) H.S.Irwin & Barneby~~*Lam.*~~, and *Leucaena leucocephala* (Lam.) de Wit~~*(L.) Benth.*~~, which grew naturally. The farming was resumed, and cotton (*Gossypium hirsutum* L.) and banana (*Musa acuminata spp.*) were planted from 1982 to 2000. From 2000 to 2009, successive annual crops per year of cotton, followed by mung bean (*Vigna radiata*

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(L.) R. Wilczek), and sesame (*Sesamum indicum* L.), followed by soybean (*Glycine max* L.), were rotated under conventional plough-based management before the establishment of the three experiments. Mineral fertilizers such as NPK (15-15-15), ammonium phosphate (16-20-0), and potassium chloride (0-0-60) were applied to the crops without lime application. T~~t~~he soil of the study site is classified as a red Oxisol (USDA, 1999) or a Ferralsol in the world reference base (WRB) for soil resources (IUSS Working Group WRB, 2015), with 1.3% sand, 29% silt, and 69% clay in the 0–20 cm and gradually increasing with soil depth to 78 % clay at 20–100 cm. The clay fraction is mainly made of kaolinite (Hok et al., 2015). The land on the site is flat, the land slope ~~(~~is < 1%~~)~~. Prior to the establishment of the three experiments in 2009, the average SOC and TN stocks in the 0–20 cm layer were 33.6 Mg C ha^{-1} and 3.33 Mg N ha^{-1}, respectively. The research site's climate is defined as tropical monsoon, corresponding to the Am Köppen climate classification, with two main seasons: the wet season from May to October and the dry season from November to April. The mean annual temperature from 2009–2021 was 27.5°C, while the average annual minimum and maximum temperatures were 22°C and 35°C, respectively. The annual rainfall ~~during ~~from 2009–202~~the last ~~1~~3 years~~ ranged between 1,650 and 2,000 mm.

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2.2 Experimental design, treatment description, and crop management

The detailed history of the research site, experimental design, treatment description, and fertilizer application were reported in Hok et al., (2015) and Pheap et al., (2019). Our study covers three separate experiments, implemented in 2009, including (i) maize (*Zea mays* L.) (which was a former rice (*Oryza sativa* L.)-based trial from 2009 to 2019 and shifted to maize-based trial in 2020), (ii) soybean~~ (*Glycine max* L.) ~~, and (iii) cassava (*Manihot esculenta* Crantz)-based cropping system trials, hereafter called MaiEx, SoyEx, and CasEx, respectively. These represent the most important annual upland crops in

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Cambodia as well as in some Southeast Asian countries. Each~~The~~ experiment~~s~~ is~~are~~ arranged in a randomized complete block design ~~(RCBD)~~ with three replicates. The elementary plot dimensions are 8 m x 37.5 m, equivalent to 300 m^2. Each experiment consists of three~~four~~ ~~(4)~~ treatments including:~~.,:~~ (1~~i~~) monocropping under conventional tillage (CTM), in which the main crops, i.e., maize (Mz), soybean (Sb), ~~and~~ or cassava (Cs), were~~are~~ mono~~-~~cropped with land preparation done by disc plough~~w~~ing (CTM-Mz, CTM-Sb, and CTM-Cs)~~.~~;~~;~~ (2~~ii~~) monocropping under ~~no-till~~NT~~age mulch-based cropping~~ systems with the use of cover crops (NTM), in which the main crops (maize, soybean, ~~and~~ or cassava) were~~are~~ cropped in a one-year frequency pattern ~~under CA management (NT1-Mz, NT1-Sb, and NT1-Cs)~~ with no soil tillage ~~along~~ and with addition of cover crops (NTM-Mz, NTM-Sb, and NTM-Cs)~~.~~; and~~s;~~ (3~~iii~~) ~~and (iv):~~ ~~NT were the~~ bi-annual rotation~~systems~~ of ~~in which~~ the main crops under NT systems with the use of cover crops (NTR), where the main crops were presented every year in two separate elementary plots designated as NTR1 and NTR2~~(i.e., soybean and cassava), were grown in a bi-annual rotation with maize in the case of SoyEx (NT2-Sb, NT3-Sb) and CasEx (NT2-Cs, NT3-Cs), respectively, while the maize was grown in a bi-annual rotation with soybean in the case of MaiEx (NT2-Mz, NT3-Mz) under CA management along and with addition of cover crops~~. For treatment (3) of SoyEx and CasEx, represented by NTR1-Sb and NTR1-Cs, respectively, the main crops (i.e., soybean and cassava) were grown in a bi-annual rotation with maize, represented by NTR2-Sb and NTR2-Cs for SoyEx and CasEx, respectively. For the treatment (3) of Mai-Ex, the main crop (i.e., maize represented by NTR1-Mz) was grown in a bi-annual crop rotation with soybean,~~s~~ represented by NTR2-Mz (Table 1). Under all the NT systems, the species, sowing dates, and methods of cover crop establishment varied depending on the design of treatments for each experiment, the types and cycles of the main crops, and the species and cycles of the cover crops (Table 1). For instance, stylo (*Stylosanthes guianensis* (Aublet) Sw.) and Brachiaria (*Brachiaria ruziziensis* R.Germ. & C.M.Evrard) were associated with rice and soybean, respectively, by manual broadcasting at the full flowering stage of rice before the end of September and at the first yellow leaves of soybean in the mid of October. Stylo was associated by line sowing with a NT planter at the same date of maize cultivation and 20 days after planting for cassava. In addition, if the development and/or density of the cover crop sown the previous year were considered insufficient, short cycle cover crop species, i.e., pearl millet (*Pennisetum typhoides* (L.) Morrone) or sorghum (*Sorghum bicolor* (L.) Moench), was sown alone or mixed with cowpea (*Vigna unguiculata* (L.) Walp. and su~~n~~nnhemp (*Crotalaria juncea* L.) at the beginning of the rainy season (in the first week of May). Cover crops were then grown for 60–75 days to increase the biomass inputs prior to the cultivation of the main cycle of rice, soybean, or maize (Table 1).

The establishment and harvest of the main crops varied depending on the species. For maize, upland rice, and soybean, with a life cycle of approximately 110–120 days, these crops were mainly seeded between the last week of June to mid-July and harvested between mid-October and mid-November, whereas cassava was planted in early May and harvested around 10 months old in the mid-February of the following year.

For main crop residue management in MaiEx and SoyEx, all crop residues were retained in the soil in all the tillage systems. In CasEx, under CTM-Cs, all the cassava fallen leaves and branches were retained in the soil, while 100% of the cassava main stems and original cuttings were completely removed from the plot after harvest~~ under CT-Cs~~, representing standard farmers' practices. For all the NT-Cs systems, all the cassava fallen leaves and branches were returned to the soil, while 50% of the cassava main stems and 100% of the original cuttings were retained in the soil and then crimped to speed up the decomposition process and facilitate field operation implementations in the following cropping season. The residues of all the cover crops were left as mulch under all the NT systems in all the experiments.

There were a few adjustments on the cropping systems over the experimental period from 2009 to 2021, especially with the use of cover crops, crop varieties, and mineral fertilizer application types and rates. Details of main crops and cover crop successions and the cumulative amount of the aboveground biomass-C and N inputs from the crop~~s~~ residues are presented in Table 1. The C inputs were estimated from the dry aboveground biomass inputs recorded prior to the termination of the cover crops and at grains/tuber harvest for the main crops. The C and N inputs from the root systems were not recorded nor even estimated based on literature. In the case of missing data of aboveground biomass, the amount of biomass was estimated using the average of recorded data over time as reference in the case of cover crops and grain and/or tuber-aboveground biomass ratio for the main crops (e.g. rice, maize, soybean and cassava). In addition, the cumulative and annual N inputs were estimated from the amount of the cumulative and annual C inputs, respectively, by applying available C/N ratio values of each plant species that were ~~yielded~~ obtained from the C and N concentration analysis by dry combustion.

For land preparation, the CTM plots were~~is~~ ploughed twice to 15-20 cm depth using a 7-disc plough after early rains at the beginning of the wet season and then before the main crop cultivation. If sufficient early rain falls were received at the beginning of the wet season (in the 3rd week of March), s~~S~~esame ~~(*Sesamum indicum* L.)~~ and mung bean ~~(*Vigna radiata* (L.) R. Wilczek)~~ were sown manually under CTM treatment in SoyEx and MaiEx, respectively, as early-cycle cash crops (April to June) prior to the main crops, i.e., soybean or maize (from July to November). If that was not the case, the CTM plots remained fallow with

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the growth of natural grasses and broad leaves until the main cycle crops. These cropping systems represent the standard farmers' practices. Under the NT systems (NTM~~1~~, NTR1~~2~~ and NTR2~~3~~), a long cycle cover crop i.e., stylo ~~(*Stylosanthes guianensis* (Aubl.) Sw.)~~ was used as a cover crop and grown in association with the main crops. This cover crop was sown in the middle of the inter-row at 0, 15, 35 days after the sowing of the main crops, i.e., maize, cassava, rice, respectively, and by seed broadcasting at the first yellow leaves of soybean, approximately 4 weeks before harvest. In addition, if the development and/or density of the cover crop sown the previous year was considered insufficient, pearl millet ~~(*Pennisetum typhoides* (L.) Morrone)~~ or sorghum ~~(*Sorghum bicolor* (L.) Moench)~~ was sown alone for the treatments planted with soybean or mixed with sunnhemp ~~(*Crotalaria juncea* L.)~~ and cowpea ~~(*Vigna unguiculata* (L.) Walp.)~~ for the treatments planted with maize at the beginning of the rainy season as short-cycle cover crops. The cover crops were then grown for 60–75 days prior to the main cycle of rice, maize, or soybean. The main crops (rice, maize and soybean), both under CTM and all the NT ~~management~~ systems, as well as the cover crops (at the beginning of the rainy season) were sown by a NT planter (Fitarelli pulled by power tiller, Vence Tudo, or Seamato lifted or pulled by tractor). From 2009 to 2020, cassava was planted along the furrows drawn by chiselling at 0.8 m spacing to approximately 20 cm depth, and then it was planted by a NT cassava planter (Planticenter) in 2021. Under the NT systems, the cover crops were terminated by crimping followed by the application of a mix of non-selective herbicides, i.e., glyphosate [N (phosphonomethyl) glycine] and 2,4-D [2,4-dichloro-phenoxyacetic acid], at a rate of 960 and 720 g active ingredient (a.i) ha^{-1}, respectively.

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Since 2009, soil amendment was done with thermo~~-~~phosphate (16% P_2O_5, 31% CaO and 16% MgO) at the end of dry season (early April), and then basal fertilizers and top dressings on the main crops were applied with different rates of N, P, K depending on the types and phenological stage of each main crops using diammonium phosphate (18% N, 46% P_2O_5), ammonium phosphate ~~sulphate~~ (16% N, 20% P_2O_5), potassium chloride (60% K_2O), and urea (46% N). The application of the fertilizer inputs to each main crop are detailed in Table S1~~2~~ ~~in the supplementary materials~~.

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Table 1. Experiments, cropping systems and crop sequences, and associated cumulative and annual aboveground C and organic N inputs from crop residues during the experimental period (2009-2021).

Experiments and cropping systems[a]	**Crop sequences from 2009 to 2021**[b]	**C input (Mg ha^{-1})**		**N input (Mg ha^{-1})**	
		Cumulative	**Annual**	**Cumulative**	**Annual**
MaiEx					
CTM-Mz~~CT-Mz~~	**R** – Mu/**R** – Mu/**R** – Mu/**R** – Mu/**R** – **R** – **R** – **R** – **R** – **R** – **R** – **Mz** – **Mz**~~R – Mu/R – Mu/R – Mu/R – Mu/R – R – R – R – R – R – R – Mz – Mz~~	28.60	2.20	0.64	0.05
NTM-Mz~~NT1-Mz~~	*Mi*/**R** – *Mi*/**R** – *Mi*/**R** – *St*/**R** – *St*/**R** – *St*/**R** – *St*/**R** – *St*/**R** – *St*/**R** – *St*/**R** – *St*/**R**+*St* – *St*/**R**+*St* – *Mi+Su+Co*/**Mz** – *Mi+Su+Co*/**Mz**~~Mi/R – Mi/R – Mi/R – St/R – St/R – St/R – St/R – St/R – St/R – St/R – St/R+St – St/R+St – Mi+Su+Co/M – Mi+Su+Co/M~~	67.70	5.21	1.50	0.12
NTR1-Mz~~NT2-Mz~~	*Mi*/**R** – *Mi+Su+St*/**Mz** – *Mi+Su+St*/**R** – *St*/**Mz**+*St* – *St*/**R**+*St* – *St*/**Mz**+*St* – *St*/**R**+*St* – *St*/**Mz**+*St* – *St*/**R**+*St* – *St*/**Mz**+*St* – *St/So+Su*+**R** – *Mi+Su+Co*/**Mz** – *So+Su+Co*/**Sb**~~Mi/R – Mi+Su+St/Mz – Mi+Su+St/R – St/Mz+St – St/R+St – St/Mz+St – St/R+St – St/M+St – St/R+St – St/Mz+St – St/So+Su+R – Mi+Su+Co/Mz – So+Su+Co/Sb~~	73.08	5.62	1.62	0.12
NTR2-Mz~~NT3-Mz~~	*Mi*/**Mz** – *Mi+P+St*/**R** – *Mi+Su+St*/**Mz**+*St* – *St*/**R**+*St* – *St*/**Mz**+*St* – *St*/**R**+*St* – *St*/**Mz**+*St* – *St*/**R**+*St* – *St*/**Mz**+*St* – *So+Su*/**R** – *St*/**Mz**+*St* – *So+Su+Co*/**Sb** – *Mi+Su+Co*/**Mz**~~Mi/Mz – Mi+P+St/R – Mi+Su+St/Mz+St – St/R+St – St/Mz+St – St/R+St – St/Mz+St – St/R+St – St/Mz+St – So+Su/R – St/Mz+St – So+Su+Co/Sb – Mi+Su+Co/Mz~~	70.12	5.39	1.56	0.12
SoyEx					
CTM-Sb~~CT-Sb~~	**Sb** – **Sb** – Se/**Sb** – **Sb** – Se/**Sb** – **Sb** – **Sb** – **Sb** – **Rb** – **Sb** – **Sb** – **Sb** – **Sb**~~Sb – Sb – Se/Sb – Sb – Se/Sb – Sb – Sb – Sb – Rb – Sb – Sb – Sb – Sb~~	23.18	1.78	0.52	0.04
NTM-Sb~~NT1-Sb~~	*Mi*/**Sb**+*Br* – *Mi*/**Sb**+*Br* – *Mi*/**Sb**+*Br* – *Mi*/**Sb**+*St* – *St*/**Sb**+*St* – *St*/**Sb**+*St* – *St*/**Sb**+*St* – *St*/**Sb**+*St* – *So+St*/**Rb** – **Rb**/*So*+**Sb** – *So+Su*/**Sb** – *So+Su+Co*/**Sb** – *So+Su+Co*/**Sb**~~Mi/Sb+Br – Mi/Sb+Br – Mi/Sb+Br – Mi/Sb+St – St/Sb+St – St/Sb+St – St/Sb+St – St/Sb+St – So+St/Rb – Rb/So+Sb – So+Su/Sb – So+Su+Co/Sb – So+Su+Co/Sb~~	65.09	5.01	1.45	0.11
NTR1-Sb~~NT2-Sb~~	*Mi*/**Sb**+*St* – *Mi+St*/**Mz**+*Br* – *Mi*/**Sb**+*St* – *Mi+Su*/**Mz** – *So*/**Sb**+*St* – *So+Su*/**Mz** – *So+St*/**Sb** – *So+Su*/**Mz**+*St* – *St*/**Rb** – **Rb**+*So*/**Mz** – *So+Su*/**Sb** – *Mi+Su+Co*/**Mz** – *So+Su*/**Sb**~~Mi/Sb+St – Mi+St/Mz+Br – Mi/Sb+St – Mi+Su/Mz – So/Sb+St – So+Su/Mz – So+St/Sb – So+Su/Mz+St – St/Rb – Rb+So/Mz – So+Su/Sb – Mi+Su+Co/Mz – So+Su/Sb~~	71.13	5.47	1.58	0.12

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NTR2-Sb~~NT3-Sb~~	*Mi*/**Mz**+*Br* – *Mi*/**Sb**+*St* – *Mi*+*Su*/**Mz**+*St* – *St*/**Sb**+*St* – *So*+*Su*/**Mz** – *So*+*Su*/**Sb** – *So*+*Su*/**Mz** – *So*+***Su***/**Sb** – *So*+*Su*/**Mz** – *So*+*Su*/**Sb** – *So*+*Su*/**Mz** – *So*+*Su*+*Co*/**Sb** – *Mi*+*Su*+*Co*/**Mz**~~Mi/Mz+Br – M/Sb+St – Mi+Su/Mz+St – St/Sb+St – So+Su/Mz – So+Su/Sb – So+Su/Mz – So+Su/Sb – So+Su/Mz – So+Su/Sb – So+Su/Mz – So+Su+Co/Sb – Mi+Su+Co/Mz~~	78.94	6.07	1.75	0.13
CasEx					
CTM-Cs~~CT-Cs~~	**Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs**~~Cs – Cs – Cs – Cs – Cs – Cs – Cs – Cs – Cs – Cs – Cs – Cs – Cs~~	17.64	1.36	0.39	0.03
NTM-Cs~~NT1-Cs~~	**Cs**+*St* – *St*/**Cs**+*St* – *St*/**Cs**+*St* – *St*/**Cs**+*St* – **Cs**+*St* – **Cs**+*St* – **Cs**+*St* – **Cs** – **Cs** – **Cs** – **Cs** – **Cs** – **Cs**~~Cs+St – St/Cs+St – St/Cs+St – St/Cs+St – Cs+St – Cs+St – Cs+St – Cs – Cs – Cs – Cs – Cs – Cs~~	46.92	3.61	1.04	0.08
NTR1-Cs~~NT2-Cs~~	**Cs**+*St* – *Mi*+**Mz**+*St* – *St*/**Cs**+*St* – *Mi*+*Su*/**Mz**+*St* – *St*/**Cs**+*St* – *St*/**Mz**+*St* – *St*/**Cs** – *St*/**Mz**+*St* – *St*/**Cs** – *So*+*Su*/**Mz** – *So*+*Su*/**Cs** – *Mi*+*Su*+*Co*/**Mz** – **Cs**~~Cs+St – Mi+Mz+St – St/Cs+St – Mi+Su/Mz+St – St/Cs+St – St/Mz+St – St/Cs – St/Mz+St – St/Cs – So+Su/Mz – So+Su/Cs – Mi+Su+Co/Mz – Cs~~	64.25	4.94	1.43	0.11
NTR2-Cs~~NT3-Cs~~	*Mi*/**Mz**+*St* – *St*/**Cs**+*St* – *Mi*+*Su*/**Mz**+*St* – *St*/**Cs**+*St* – *Mi*+*Su*/**Mz**+*St* – *St*/**Cs**+*St* – *St*/**Mz**+*St* – *St*/**Cs** – *So*+*Su*/**Mz** – *So*+*Su*/**Cs** – *So*+*Su*/**Mz** – *Cs* – *Mi*+*Su*+*Co*/**Mz**~~Mi/Mz+St – St/Cs+St – Mi+Su/Mz+St – St/Cs+St – Mi+Su/Mz+St – St/Cs+St – St/Mz+St – St/Cs – So+Su/Mz – So+Su/Cs – So+Su/Mz – Cs – Mi+Su+Co/Mz~~	67.10	5.16	1.49	0.11

[a] MaiEx: maize-based cropping system trial; SoyEx: soybean-based cropping system trial; and CasEx: cassava-based cropping system trial; CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no-till mulch-based cropping systems associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems under NT systems with no-till mulch-based cropping systems associated with different crop sequences.~~no-till, NT1, NT2, and NT3 refer to no-till mulch-based cropping systems associated with different crop sequences.~~

[b] Br: brachiaria (*Brachiaria ruziziensis* R.Germ. & C.M.Evrard); Co: cowpea (*Vigna unguiculata* (L.) Walp.); Cs: cassava (*Manihot esculenta* Crantz); Mi: millet (*Pennisetum glaucum* (L.) R.Br.); Mu: Mungbean (*Vigna radiata* (L.) R. Wilczek) Mz: maize (*Zea mays* L.); P: pigeon pea (*Cajanus cajan* L.); R: rice (*Oryza sativa* L.); Rb: ricebean (*Vigna umbellata* (Thunb.) Ohwi & H. Ohashi); Sb: soybean (*Glycine max* L.); Se: sesame (*Sesame indicum* L.); So: Sorghum (*Sorghum bicolor* (L.) Moench); St: stylo (*Stylosanthes quianensis* (Aubl.) Sw.); Su: sunnhemp (*Crotalaria juncea* L.).~~;~~ The letters in bold, underlined, and italicized indicate the main crops, cash crops, and cover crops, respectively. "–" indicates the period between the year; "/" indicates relay cropping with varying planting dates; and "+" indicates crops planted in association (same or staggered sowing dates). The C inputs were estimated from the amount of aboveground biomass of each crop; the belowground biomass was not included.

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~~**Table 2**. Mineral fertilizer rates applied to the main crops during the experimental period (2009-2021).~~

~~**Annual mineral fertilizer rates (kg ha^{-1})[a]**~~	~~**Crops**~~	~~**Year**~~													~~**Total fertilizer input**~~
		~~**2009**~~	~~**2010**~~	~~**2011**~~	~~**2012**~~	~~**2013**~~	~~**2014**~~	~~**2015**~~	~~**2016**~~	~~**2017**~~	~~**2018**~~	~~**2019**~~	~~**2020**~~	~~**2021**~~	
~~N in $CO(NH_2)_2$~~	~~Cassava~~	~~92~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~69~~	~~920~~
	~~Maize~~	~~92~~	~~69~~	~~69~~	~~69~~	~~69~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~736~~
	~~Rice~~	~~69~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~			~~529~~
	~~Soybean~~	~~23~~	~~23~~	~~23~~	~~23~~	~~23~~									~~115~~
~~N in $(NH_4)_2SO_4$~~	~~Maize~~						~~24~~	~~24~~	~~24~~	~~24~~	~~24~~	~~24~~	~~24~~	~~24~~	~~192~~
~~N in $(NH_4)_2HPO_4$~~	~~Soybean~~						~~18~~	~~18~~	~~18~~	~~18~~	~~18~~	~~18~~	~~18~~	~~18~~	~~144~~
~~P_2O_5~~	~~All crops~~	~~80~~	~~32~~	~~32~~	~~32~~	~~32~~	~~32~~	~~32~~	~~32~~	~~32~~	~~32~~	~~32~~	~~0~~	~~0~~	~~400~~
~~P in $(NH_4)_2SO_4$~~	~~Maize~~						~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~240~~
~~P in $(NH_4)_2HPO_4$~~	~~Soybean~~						~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~46~~	~~368~~
~~K_2O~~	~~Cassava~~	~~60~~	~~90~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~810~~
	~~Maize~~	~~60~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~420~~
	~~Rice~~	~~60~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~	~~30~~			~~360~~
	~~Soybean~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~60~~	~~780~~

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~~$CO(NH_2)_2$: Urea (46.0.0); $(NH_4)_2SO_4$: Ammonium sulphate (16.20.0); $(NH_4)_2HPO_4$: Diammonium phosphate (18-46-0); P_2O_5: Thermo phosphate (0.18.0); and K_2O: Potassium chloride (0.0.60).~~

~~2.247~~2.3 Soil sampling and processing

The study was a diachronic analysis from 2011 to 2021. In 2009, prior to the establishment of the experiments, soil and bulk density (ρb) samples were collected as the pre-experiment (PE) from three randomly selected sampling points per replicate of each experimental location at four depths: 0–5, 5–10, 10–20, and 20–30 cm. The individual soil samples from the same depth and replicate were composited, resulting in three composites per depth and per experiment. The composite samples were oven dried at 40°C and sieved through a 2mm mesh for chemical property analysis. Bulk density samples were collected using core samplers of 5 cm in diameter and 5 cm in height, oven dried at 105°C for 48 h. The SOC and TN stocks of PE in 2009 in the top 0–20 cm were 33.3, 35.0, and 32.4 Mg C ha^{-1} and 3.34, 3.41, and 3.26 Mg N ha^{-1} in MaiEx, SoyEx, and CasEx, respectively (Fig. S1).

In November 2011, soil sampling was conducted to assess the early effects of tillage systems on soil organic C and N concentrations and stocks. The details of the sampling are described in Hok et al., (2015). Briefly, two pits (1m x 1m) were opened per elementary plot for soil and ρb sample collection. Individual samples for chemical analysis were collected from two undisturbed sides of each pit at 0–5, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. The individual samples from the same depth and the same pit were composited, and as a result, two composite samples per layer were collected per elementary plot. The composites were oven-dried at 40°C before being softly disrupted, sieved through a 2-mm sieve, and homogenized. Soil bulk density samples were taken from the same two undisturbed sides of each pit at the same soil depths as for SOC analysis using core samplers of 5 cm in diameter and 5 cm in height. The soil cores were oven-dried at 105°C for 48 h. ~~Similarly, in 2011, six subplots were delimited for soil~~

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~~sampling in an area of roughly 17 ha in the adjacent reference vegetation (RV), which served as a baseline for comparison with the three cropping systems. The reference vegetation site was located approximately 500 m from the experimental plots. The vegetation composition of RV was an old coffee plantation grown under the shade of *Leucaena glauca* (Lam.) de Wit that was planted in 1990. The crop history here was the same as that of the experimental plots from 1937 to 1990 after the conversion of the natural forest to cropland.~~

In December 2021, we re-sampled the soil to assess the changes in ρb, SOC and N concentrations and stocks ten years after the study conducted by Hok et al., (2015). The samples were collected at the same 7 layers. From each treatment and replicate, we collected four individual samples by an automatic soil column cylinder auger (a gasoline-powered percussion hammer Cobra TT with inner diameter of 85 mm, Eijkelkamp, the Netherlands) in a diagonal “X” shape from four points within each plot, avoiding overlapping on the pits opened in 2011. In addition, we dug a 1 m x 1 m pit in the middle of each plot for sample collection; three individual soil samples and three ρb cores were collected from three undisturbed sides of the pit at each depth. Soil samples were air-dried at room temperature, gently broken down, and sieved through a 2 mm mesh sieve. Finally, the seven individual samples from the same layer were mixed and homogenized to make a composite sample per elementary plot. The samples of ρb were oven-dried at 105°C for 48 h.

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~~2.248~~2.4 Soil organic C and total N analyses

The concentrations of SOC and ~~total~~ TN ~~concentration~~ of the soil samples collected in 2009 and 2011 were determined by dry combustion using an elemental CN analyzer (TruSpec CN, LECO, St. Joseph, USA). The details of the analysis were described in Hok et al., (2015). Sub-samples of the composite soils (n = 3 per layer) collected in 2021 were finely ground (<150 µm) before analysis for total C and N by dry combustion using the LECO® CHN628 analyzer at the Sustainable Agroecosystems Lab, ETH Zurich University, Switzerland.

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~~2.249~~2.5 Soil organic C and total N stocks calculation

In this Oxisol, there was no coarse fraction (i.e. gravels) left after sieving at 2 mm. Therefore, the bulk density of soil equals the bulk density of fine earth. To avoid inaccurate stock calculation due to differences in bulk density between treatments when using the fixed depth method, the equivalent soil mass (ESM) approach was applied to compute SOC and TN stocks (Ellert and Bettany, 1995; Von Haden et al., 2020; Fowler et al., 2023). Since the ρb of the treatments differed between the two sampling years (2011 and 2021) ~~and the reference vegetation~~ at each sampling depth (Table S2~~1 in the supplementary materials~~), we defined the reference soil mass as the lowest soil mass observed at each sampling depth, regardless of sampling years, cropping systems or land use. For this reference, soil mass layers (480, 518, 1061, 1873, 1766, 1809, and 1779 Mg ha^{-1}) corresponded to the depth layers (0–5, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm, respectively). We applied these reference soil masses to compute the SOC and TN stocks in 2021 and recalculated the stocks of the PE~~, RV~~ and the treatments of the three experiments collected in 2009 and 2011.

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To correct for differences in ρb, SOC and TN stocks were computed according to Eq. 1 and 2.

$$M_{(Soilmin,i)} = \rho b_{(i)} \times T_{(i)} \times 1000 \qquad (eq. 1)$$

$$SOC\ or\ TN\ stock = \sum_{i=1}^{n} [(M_{(soilmin,i)} \times conc._{(i)}) + ((M_{(soil,i)} - M_{(soilmin,i)}) \times conc._{(i-1)})] \times 0.001 \qquad (eq.\ 2)$$

Where: $M_{(soilmin,i)}$ is the minimal soil mass per unit area in the ith layer (Mg ha^{-1}) recorded over the treatments and used as a reference. $\rho b_{(i)}$ is the bulk density of the ith layer (g cm^{-3}). $T_{(i)}$ is the thickness of the ith layer (m). $conc._{(i)}$ is the concentration of SOC in ith layer. $conc._{(i-1)}$ is the concentration of SOC in i - 1th layer. $M_{(soil,i)}$ is the designated soil mass of each layer (i.e., the maximum soil mass). The numbers 1000 and 0.001 are unit conversion coefficients.

We defined delta ~~-~~stock (Δ) of SOC and TN, as the stock change within the same treatment and depth between 2021 and 2011 sampling years (diachronic) and calculated it as follows:

$$\Delta SOC\ or\ TN\ stock.diach = SOC\ or\ TN stock_{treat.\cancel{ment}\ (i)2021} - SOC\ or\ TN stock_{treat.\cancel{ment}\ (i)2011} \qquad (eq.3)$$

Where: i represents the treatments.

To compare the synchronic and diachronic approaches for SOC stock change, the stock change estimated by the synchronic approach was computed as follows using the CTM treatment as the control treatment:

$$\Delta SOCstock.synch = SOCstock_{NT(i)2021} - SOCstock_{CTM2021} \qquad (eq.4)$$

Where: NT(i) represents NTM~~1~~, NTR1~~2~~, and NTR2~~3~~ treatments.

The SOC and TN stock change (accumulation or loss) rates (Mg C or N ha^{-1} yr^{-1}) of each treatment were calculated by dividing Δ SOC or TN stock by the number of years between the 1st and 2nd samplings (10 years):

$$SOC\ or\ TN\ stock\ chang{-}e\ rate_{treatment(i)} = \frac{\Delta SOC\ or\ TN\ stock_{treatment(i)}}{10} \quad (eq.5)$$

~~2.250~~2.6 Particle-size fractionation of soil organic matter

The soil organic C was physically fractionated using a sub-sample of the composite soil for all the treatments and seven depths. The particle-size fractionation was implemented in accordance with the procedure described in Hok et al., (2015). Briefly, 40 g of soil samples were dispersed in a solution of 1.25 g of sodium hexametaphosphate and 100 mL of deionized water and stored at 10 °C for 16 hours. The sample was then horizontally shaken at 100 rpm for 8 hours with three 10-mm-diameter agate balls. The soil mixture was wet-sieved with deionized water through a 53-µm sieve to get the proportion of particulate organic matter (POM) sized between 53µm and 2,000µm. The <–53-µm fraction was flocculated with 2-g $CaCl_2$ in a 1-L glass cylinder and left overnight for sedimentation. The supernatant was syphoned after full sedimentation. This <-53-µm fraction is made up of mineral-associated organic matter (MAOM). The two fractions were oven-dried at 40°C until reaching constant weight and finely ground for determining SOC and TN concentrations by dry combustion using the LECO® CHN628 analyzer at the Sustainable Agroecosystems Lab, ETH Zurich University, Switzerland.

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~~2.251~~2.7 Statistical analysis

Statistical analysis was cond~~mp~~ucted using R software, version 4.3.1 (Core Team, 2023). Linear mixed models (*lmerTest* package) were fitted on all data: sampling years, soil depths, and treatments were defined as the fixed factors, while the replicates were defined as the random factors. Prior to the analysis, the normality of each variable was checked by Shapiro’s test. Then we applied Levene’s test to check the homoscedasticity of the data. A diachronic approach was used to assess statistical significance between the two sampling years (i.e., 2021 vs. 2011) of the same treatment at the same soil depth by analysis of variance with Fisher tests (degrees of freedom calculated by Satterthwaite method), computing of estimated marginal means (EMMs) and p-value adjustment using the Tukey method. The same approach was used to compare SOC stocks between treatments in the same sampling year, calculated at equivalent soil mass and using the synchronic approach. In addition, we applied the same statistical procedures to assess the statistical significance of cumulative SOC and TN stocks.

3 Results

The effects of cropping systems on the concentrations, stocks of SOC and TN as well as their fractions in the physical size classes between 2011 and 2021 varied among the three experiments and across the soil profile.

3.1 Impacts of ~~tillage and~~ c~~C~~ropping system~~ effect~~s on SOC ~~and N~~ concentrations and stock~~s~~

~~3.1~~3.1.1 SOC concentration

The SOC concentration~~s~~ of ~~SOC~~ all the treatments~~d N~~ in 2011 and 2021 was~~re presented~~ highest in~~ Fig. 1 and Fig. 2, respectively, with~~ the ~~duplica~~t~~es pr~~op~~v~~soil (0–5 cm) ~~ded in Table S2~~ and decreased with

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soil depth ~~S3 in the supplementary materials. Table 3 and 4 show the SOC and N stocks in 2021 and the stock change rate between 2011 and 2021, respectively. The SOC and N stocks~~ in ~~2011~~ all the experiments (Fig.1 with ~~re provided in~~ Table S3~~4 in the supplementary~~ as duplication)~~materials~~.

~~Maize-based experiment~~

~~The SOC concentration of all the treatments in 2011 and 2021 was highest in the topsoil (0–5 cm) and decreased with soil depth (Fig. 1A and 1B). From 2011 to 2021, SOC concentration under NT-Mz crop rotation systems (average of NT2-Mz and NT3-Mz) significantly increased by 50%, 24%, and 15% at 0–5, 5–10, and 10–20 cm depth, respectively. Significant increase was still observed under NT2-Mz at 20–40 cm depth. NT1-Mz significantly increased SOC concentration over the whole soil profile by 68%, 21%, 16%, 17%, 23%, and 16% at 0–5, 5–10, 20–40, 40–60, 60–80, and 80–100 cm, respectively (Fig. 1B) when compared between 2021 and 2011. In the case of CT-Mz, except for the significant increase observed in the 10–20 cm layer, the SOC concentration remained neutral at 0–10 and 20–80 cm, then significantly decreased at 80–100 cm (Fig. 1A and 1B).~~

Over a 10-year period of historical cropping sequences from 2011 to 2021, ~~the~~all the NT cropping systems had significant ~~r~~effe~~spons~~ects (*p* < 0.05) ~~of SOC stock and~~ in the increase of ~~ts distribution varied depending on the tillage and cropping systems (Table 3).~~ SOC ~~sto~~c~~k under NT-Mz cr~~o~~p rotatio~~n ~~systems inc~~c~~r~~entration~~ased by 50%, 26%, and 15%, equivalent~~. ~~to a gain of 4.6, 2.6, and 2.2 Mg C ha^{-1} at 0–5, 5–10, and 10–20 cm depth, respectively. Unlike SOC concentration, NT1-Mz only significantly increased SOC stock in the top soils by 68% and 26%, equivalent to 6.1 and 2.2 Mg C ha^{-1} in the 0–5 and 5–10 cm, respectively. Despite CT-Mz significantly accumulated SOC stock in the tilled layers (5–10 and 10–20~~

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~~cm), significant reductions were found in the 60–80 and 80–100 cm depths (Table 3).~~On the other hand, the

~~At the first sampling in 2011,~~ SOC ~~stock in 0–20 cm depth under RV was significantly ($P < 0.05$) higher at 17%, 21%, and 22% than under~~ concentration under CT-M~~z~~ remained stable with exception of a few significant ~~, NT1-Mz, and NT-Mz crop rotation systems,~~ increas~~p~~es detected in the tilled layers in ~~etively.~~ ~~In 2021, SOC stock under CT-~~MaiEx and CasEx (Fig. 1). ~~z and all the NT-Mz did not differ ($P < 0.05$) from RV. SOC stock was fully recovered under NT-Mz crop rotation systems and even surpassed the RV's stock by +0.64 Mg C ha^{-1} under NT1-Mz, while the difference with RV decreased from 17 to 8% under CT-Mz (Fig. 3A).~~

~~Considering a 100 cm as a single stratum, all the NT-Mz cropping systems significantly increased SOC stock, with accumulation rates ranging from 0.86 to 1.47 Mg C ha^{-1} yr^{-1}, while it was not the case in CT-Mz (Table 3).~~

~~Over 10 years of cultivation, all the NT-Mz systems significantly increased N concentration in the top 0–5 cm depth (32% in NT-Mz crop rotation systems and 44% in NT1-Mz), but soil N significantly decreased by -24% in NT1-Mz at 40–60 cm and at least from -18 to -21% in NT-Mz crop rotation systems from 40 to 100 cm. In CT-Mz, soil N concentration remained neutral from 0 to 40 cm, then significantly decreased in the 40–60 and 80–100 cm depths (Fig. 2A and 2B).~~

~~N stock in the soils under all the NT-Mz systems significantly increased in the uppermost soil surface (0–5 cm), remained neutral in the 5–40 cm, then significantly decreased below 40 cm (Table 4). Averaged N stock in NT-Mz crop rotation systems increased by 32%, equivalent to 0.3 Mg N ha^{-1} in the 0–5 cm, whereas there was significant reduction of -16% and -23% from 40 to 100 cm. In NT1-Mz, N stock~~

~~significantly increased in the 0–5 cm layer by 43%, equivalent to 0.4 Mg N ha~~$^{-1}$~~, then significantly reduced by -23% in the 40–60 cm. In the case of CT-Mz, N stock remained constant from 0–40 cm, then significantly declined from -14 to -24% from 40 to 100 cm (Table 4).~~

~~When RV was used as a reference (0-20 cm depth), N stock in 2011 was significantly lower by 25%, 22%, and 20% under CT-Mz, NT1-Mz, and NT-Mz crop rotation systems, respectively. In 2021, the difference in N stock decreased to 15% and 7.5% under the NT1-Mz and NT-Mz crop rotation systems, respectively, when compared with RV. In contrast to NT-Mz, N stock did not change under CT-Mz in 2021 (Fig. 3D).~~

~~Although not significant, after nearly a decade of rice-based and the recent shift to maize-based systems, soil N stock in the whole profile (0–100 cm) showed a decreasing trend by -11%, -6%, and -5%, equivalent to annual loss rates of -0.11, -0.06, and -0.06 Mg N ha~~$^{-1}$ ~~yr~~$^{-1}$ ~~under CT-Mz, NT1-Mz, and NT-Mz biannual rotation systems, respectively (Table 4).~~

~~**3.1.2** Soybean-based experiment~~

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~~After 10 years of implementation, significant increase~~ ~~($p < 0.05$)~~ ~~in SOC concentration was only observed under all the NT-Sb cropping systems (NT1-Sb, NT2-Sb, and NT3-Sb) in the top 0–5 cm with a similar increase amount of ~7.5 g C kg~~$^{-1}$ ~~soil. SOC concentration in CT-Cs remained stable across the whole profile (Fig. 1C and 1D).~~

~~SOC stock significantly increased in the surface layers (0–10 cm) under all NT-Sb systems (Table 3). SOC stock significantly increased by 3.6 Mg C ha-1 in the 0–5 cm in NT1-Sb. NT-Sb crop rotation systems (average of NT2-Sb and NT3-Sb) significantly accumulated SOC stock by 3.55 and 1.75 Mg C~~

~~ha^{-1} in 0–5 and 5–10 cm, respectively, along with a positive trend from 10 to 60 cm depth. Unlike all the NT-Sb systems, the SOC stock in the CT-Sb soil remained neutral across the whole profile (Table 3).~~

~~In 2011, RV as a reference (0-20 cm) significantly stored 13%, 14%, and 16% higher SOC stock than CT-Sb, NT1-Sb, and NT-Sb bi-annual rotation, respectively. In 2021, SOC stock increased and a 100% recovery was observed under NT-Sb biannual rotation systems, while the differences with RV dropped to 9% and 5% under CT-Sb and NT1-Sb, respectively, although not significant (Fig. 3B).~~

~~Considering the whole profile (0–100 cm), after 10 years of cultivation, the study showed that all the NT-Sb systems increased SOC stock with annual accumulation rates ranging from 0.65 to 1.00 Mg C ha^{-1} yr^{-1} although non-significant difference was detected (Table 3).~~

~~From 2011 to 2021, all the NT-Sb systems significantly increased soil N concentration in the top 0–5 cm with a similar increase of ~0.46 g N kg^{-1} soil (Fig. 2C and 2D). Noticeably, significant decreases in N concentration were observed in the 40–60, 60–80, and 80–100 cm under NT-Sb bi-annual rotation systems and in the 60–80 and 80–100 cm depths under NT1-Sb (Fig. 2C and 2D). In contrast to NT-Sb systems, N concentration remained constant across the whole profile in soybean monocropping under conventional plough-based tillage (CT-Sb) (Fig 2D).~~

~~Over 10 years of cultivation, the N stock significantly increased in a similar amount of 0.2 Mg N ha^{-1} under all the NT-Sb systems in the top 0–5 cm. The N stock under all the NT-Sb systems remained stable from 5 to 60 cm, then significantly decreased in the 60–80 and 80–100 cm depths (Table 4).~~

In 202~~1~~1, ~~RV's soil (0-20 cm) significantly stored 23%, 20%, and 18% higher N stock than CT-Sb, NT1-Sb, and NT-Sb crop rotation systems, respectively. In 2021, N stock increased and the differences with~~

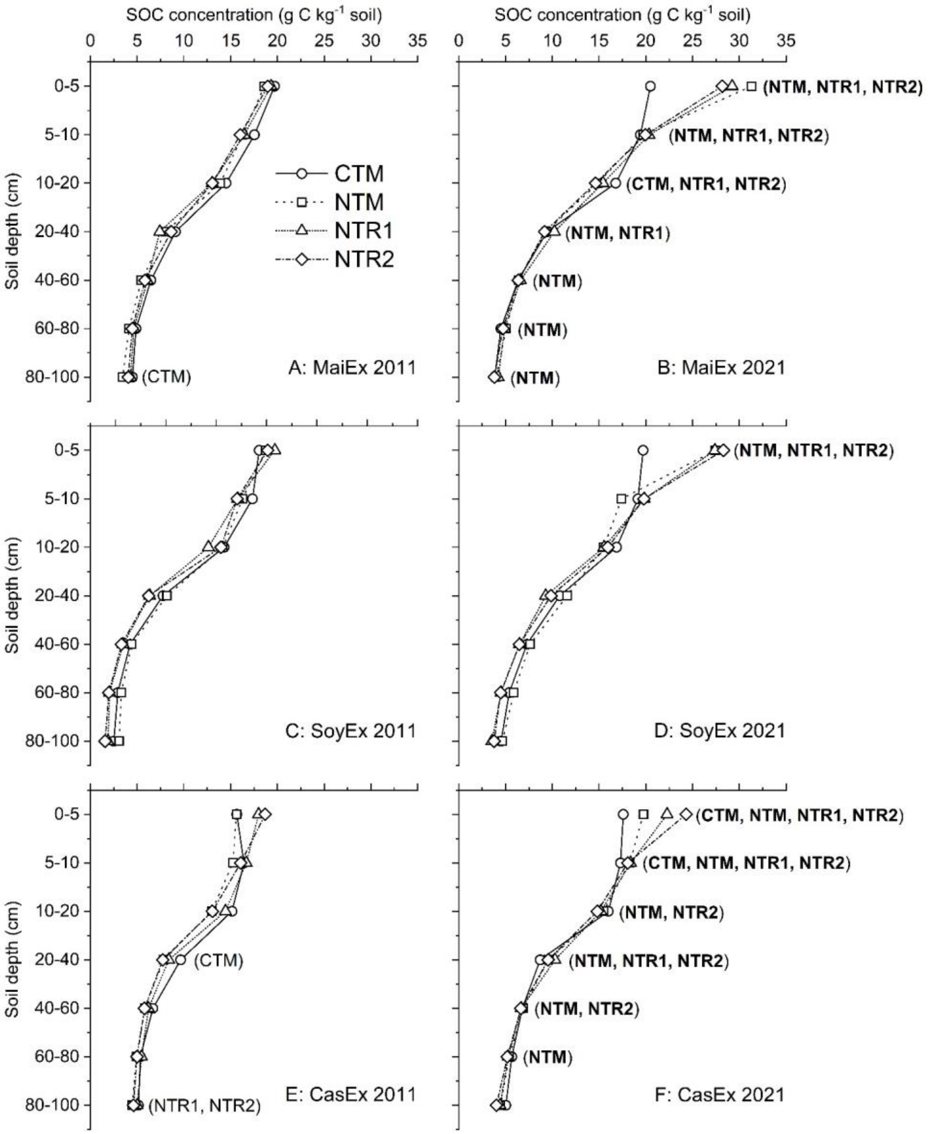
~~RV reduced to 16%, 18%, and 11% under CT-Sb, NT1-Sb, and NT-Sb crop rotation systems, respectively, although not significant (Fig. 3E).~~

~~Measured in the whole profile (0–100 cm), soybean monocropping under NT systems (NT1-Sb) significantly decreased N stock with an annual loss rate of -0.1 Mg N ha^{-1} yr^{-1}, while NT-Sb bi-annual rotation systems exhibited a decrease trend of N stock with an annual loss rate of -0.06 Mg N ha^{-1} yr^{-1} (Table 4). Despite the significant increase in the 10–20 and decrease in the 60–80 cm, N stock in CT-Sb remained stable when considering the whole profile 0–100 cm (Table 4).~~ the monocropping of main crops under NT systems in MaiEx (NTM-Mz) and CasEx (NTM-Cs) exhibited a similar trend in increasing SOC concentration significantly ($p < 0.05$) across the soil profile compared to 2011 (Figs. 1B and 1F). The SOC concentration under NTM-Mz increased by 68%, 21%, 16%, 17%, 23%, and 16% at 0–5, 5–10, 20–40, 40–60, 60–80, and 80–100 cm, respectively (Fig. 1B). The significant increase in SOC concentration under NTM-Cs was detected from 0 to 80 cm with a gain of 26%, 20%, 19%, 22%, 18%, and 10% in the 0–5, 5–10, 10–20, 20–40, 40–60, and 60–80 cm, respectively (Fig. 1F).

When compared to 2011, the bi-annual rotation of main crops under NT systems in MaiEx (NTR1-Mz and NTR2-Mz) and CasEx (NTR1-Cs and NTR2-Cs) significantly ($p < 0.05$) increased SOC concentration from the surface down to subsoil depth in 2021 (Figs. 1B and 1F). On average NTR-Mz (average of NTR1-Mz and NTR2-Mz), significantly increased SOC concentration by 50%, 24%, and 15% at 0–5, 5–10, and 10–20 cm depth, respectively. Significant increase was still observed under NTR1-Mz at 20-40 cm depth (Fig. 1B). In 2021, among the two treatments of NTR-Cs crop rotation systems (NTR1-Cs and NTR2-Cs), NTR2-Cs significantly increased SOC concentration from the top 0 to 60 cm by 30%, 12%, 13%, 23%, and 15% in the 0–5, 5–10, 10–20, 20–40, and 40–60 cm, respectively, while a significant decrease of -13% was recorded in the 80–100 cm depth (Figs. 1E and 1F). Under NTR1-Cs, significant increases in SOC concentration were observed up to 40 cm depth with a gain of 24%, 10%, and 23% in 0–5, 5–10, and 20–40 cm, respectively, with a significant decrease by -12% in 80–100 cm depth (Figs. 1E and 1F).

Unlike MaiEx and CasEx, the significant increase ($p < 0.05$) in SOC concentration under all the NT cropping systems in SoyEx (NTM-Sb, NTR1-Sb, and NTR2-Sb) in 2021 was only observed in the top 0–5 cm with a similar increase amount of ~7.5 g C kg^{-1} soil (Fig 1D).

Over a decade of monocropping of main crops under conventional tillage in all the experiments (CTM-Mz, CTM-Sb, and CTM-Cs), the SOC concentration remained ~~neutral~~stable overall, with the exception of a few significant increases detected in the tilled layers in MaiEx (CTM-Mz at 10–20 cm) and CasEx (CTM-Cs at 0–5 and 5–10 cm) (Figs. 1B, 1D, and 1F).



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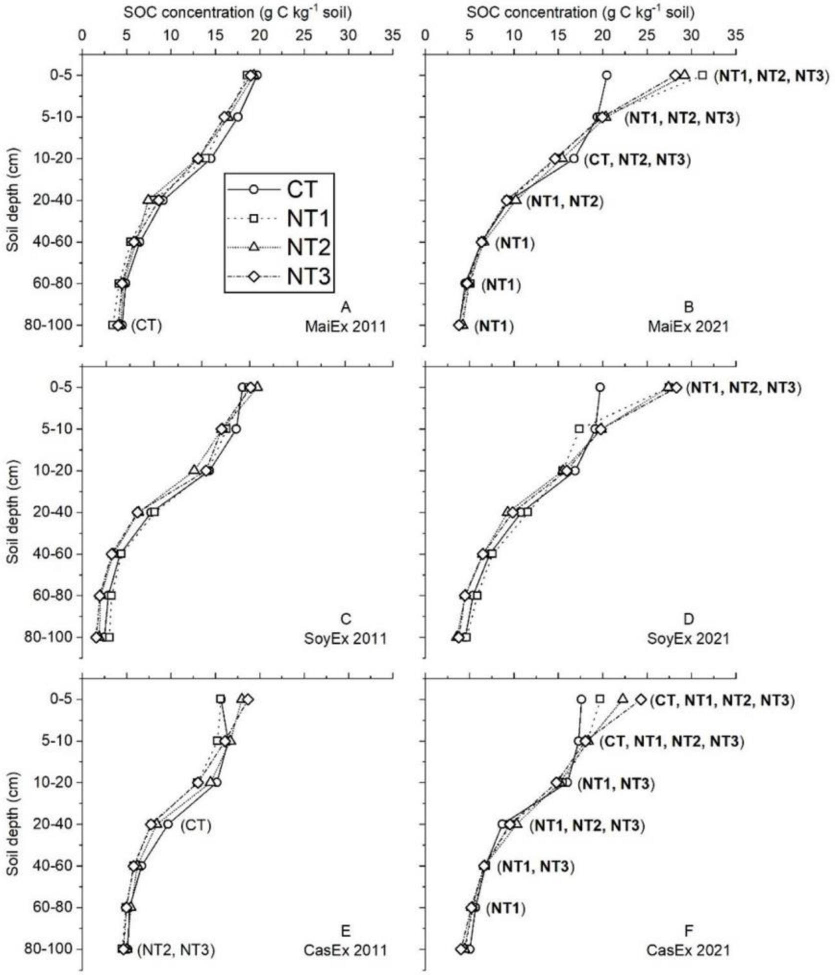

Figure 1. SOC concentration distribution across the soil profile (0~~–~~–100 cm) of the treatments ~~in 2011 and 2021~~ under different ex~~cro~~peri~~ping syste~~ments in 2011 and 2021. CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no--till mulch-based cropping systems associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems

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under NT systems with no-till mulch-based cropping systems associated with different crop sequences~~CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till associated with different cropping systems~~ as described in Table 1. A: MaiEx 2011 – SOC concentration of the treatments in maize-based trial measured in 2011; B: MaiEx 2021 – SOC concentration of the treatments in maize-based trial measured in 2021; C: SoyEx 2011 – SOC concentration of the treatments in soybean-based trial measured in 2021; D: SoyEx 2021 – SOC concentration of the treatments in soybean-based trial measured in 2021; E: CasEx 2011 – SOC concentration of the treatments in cassava-based trial measured in 2011; and F: CasEx 2021 – SOC concentration of the treatments in cassava-based trial measured in 2021. Treatment(s) in bold within the brackets indicate the gain and significant ($p < 0.05$) difference in concentrations between 2011 and 2021 in the same treatment at the same soil depth.

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3.1.2 SOC stock

From 2011 to 2021, there were significant ($p < 0.05$) increases in SOC stock~~ and vertical distribution~~, which varied depending on tillage, cropping systems, and the experiments (Table 2 and Table S5). In 2021, in the case of MaiEx, the SOC stock under NTR-Mz crop rotation systems (average of NTR1-Mz and NTR2-Mz) significantly ($p < 0.05$) increased by 4.6, 2.6, and 2.2 Mg C ha^{-1} at 0–5, 5–10, and 10–20 cm depth, respectively. NTR1-Mz showed a significant increase in SOC stock at a deeper profile at 20–40 cm, with a gain of 4.5 Mg C ha^{-1} (Table 2 and Table S5). In the case of CasEx, the soils under NTR-Cs crop rotation systems (average of NTR1-Cs and NTR2-Cs) in 2021 significantly ($p < 0.05$) increased SOC stock by an average of 2.4, 1.1, 1.4, and 2.9 Mg C ha^{-1} in 0–5, 5–10, 10–20, and 20–40 cm, respectively, but significantly decreased by an average of -0.9 Mg C ha^{-1} in 80–100 cm (Table 2 and Table S5). For SoyEx, NTR-Sb crop rotation systems (average of NTR1-Sb and NTR2-Sb) significantly accumulated SOC stock by an average of 3.55 and 1.75 Mg C ha^{-1} in 0–5 and 5–10 cm, respectively, along with a positive trend from 10 to 80 cm depth (Table 2 and Table S5).

Unlike SOC concentration, the significant effect of increasing SOC stock of the monocropping of main crops under NT systems varied across the three experiments (Table 2). NTM-Cs showed the significant

($p < 0.05$) accumulation of SOC stock by 2.0, 1.6, 2.5, and 2.2 Mg C ha^{-1} in 0–5, 5–10, 10–20, and 20–40 cm, respectively (Table 2 and Table S5). NTM-Mz significantly increased SOC stock in the surface layers (0–10 cm) by 6.1 and 2.2 Mg C ha^{-1} in the 0–5 and 5–10 cm, respectively, while the NTM-Sb significantly increased the stock by 3.6 Mg C ha^{-1} in the 0–5 cm (Table 2 and Table S5).

In the case of monocropping of main crops under conventional tillage, despite there were a few significant increases in SOC stock were detected in the till layers in CTM-Mz (MaiEx) by 0.9 and 2.3 Mg C ha^{-1} in the 5–10 and 10–20 cm, respectively, the significant decline in SOC stock was observed below 60 cm with the decreasing by approximately -1.2 Mg C ha^{-1} at the 60–80 and 80–100 cm depth (Table 2). For CasEx and SoyEx, despite the significant increase in SOC stock was observed in CTM-Cs from 0 to 20 cm, the accumulation rate was 2 times lower than those NT systems, while no significant changes were recorded under CTM-Sb (Table 2).

~~Although non-significant, when compared with PE~~Over the 10-year period from 2011 to 2021, considering a 100 cm layer as a single stratum, all the NT cropping systems significantly increased SOC stock, with accumulation rates ranging from 0.86 to 1.47 and 0.70 to 1.07 Mg C ha^{-1} yr^{-1} Mg C ha^{-1} yr^{-1} for CA-Mz and CA-Cs, respectively (Table 2). Although non-significant ~~($p > 0.05$)~~ difference detected, ~~the study showed that~~ all the NT-Sb systems increased SOC stock with annual accumulation rates ranging from 0.65 to 1.00 Mg C ha^{-1} yr^{-1} (Table 2). Despite there were a few significant increases in SOC stock were observed under CTM, the whole profile SOC stock in all the CTM (CTM-Mz, CTM-Sb, and CTM-Cs) remained ~~neutral~~stable in 2021 (Table 2).

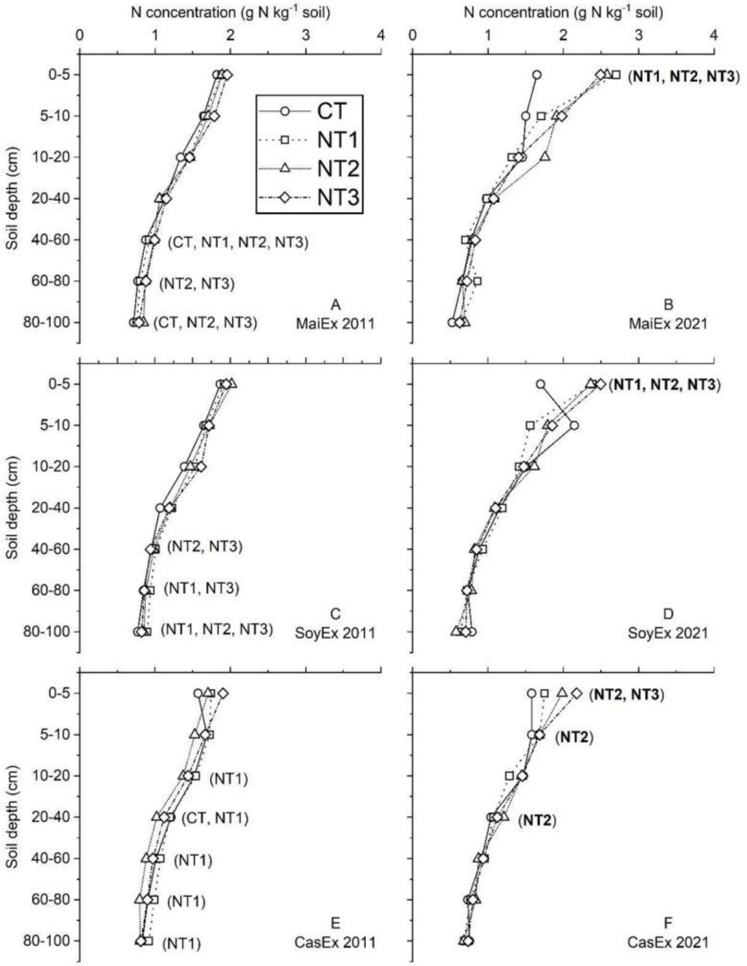
Table 2. Mean SOC stocks in 2021 and SOC stock change rate between 2021 and 2011.

Experiments[a]	**Approximate soil depth (cm)**	**Cropping systems**[b]							
		CTM	**NTM**	**NTR1**	**NTR2**	**CTM**	**NTM**	**NTR1**	**NTR2**
		SOC stock in 2021 (Mg C ha^{-1})				**SOC stock change rate 2021-11 (Mg C ha^{-1} yr^{-1})**			
MaiEx	0-5	9.83 (±0.19)	15.01 (±0.38) A	14.03 (±0.32) A	13.52 (±0.54) A	0.04 (±0.03)	**0.61** (±0.06)	**0.48** (±0.02)	**0.44** (±0.02)
	5-10	10.16 (±0.18) A	10.91 (±0.11) A	11.16 (±0.06) A	10.89 (±0.46) A	**0.09** (±0.03)	**0.22** (±0.01)	**0.23** (±0.00)	**0.22** (±0.06)
	10-20	18.28 (±0.26) A	16.31 (±0.57)	17.08 (±0.07) A	16.32 (±0.69) A	**0.23** (±0.02)	0.11 (±0.06)	**0.25** (±0.04)	**0.19** (±0.09)
	20-40	19.90 (±0.72)	18.61 (±0.43)	20.28 (±0.70) A	18.64 (±0.58)	0.11 (±0.06)	0.16 (±0.07)	**0.45** (±0.08)	0.07 (±0.08)
	40-60	12.58 (±0.37)	12.18 (±0.25)	12.75 (±0.42)	12.31 (±0.19)	-0.04 (±0.03)	0.08 (±0.08)	0.10 (±0.03)	0.02 (±0.05)
	60-80	9.01 (±0.61) B	9.58 (±0.31)	9.64 (±0.48)	9.33 (±0.26)	**-0.12** (±0.02)	0.07 (±0.08)	-0.02 (±0.01)	-0.02 (±0.01)
	80-100	7.17 (±0.66) B	7.51 (±0.54)	7.97 (±0.38)	7.26 (±0.05)	**-0.13** (±0.05)	0.05 (±0.08)	-0.02 (±0.02)	-0.06 (±0.05)
	0-100	86.92 (±2.18)	90.13 (±1.82) A	92.90 (±2.30) A	88.27 (±2.11) A	0.17 (±0.15)	**1.30** (±0.38)	**1.47** (±0.11)	**0.86** (±0.20)
SoyEx	0-5	9.45 (±.0.05)	13.17 (±0.19) A	13.14 (±0.30) A	13.58 (±0.31) A	0.02 (±0.03)	**0.36** (±0.02)	**0.32** (±0.02)	**0.39** (±0.05)
	5-10	9.95 (±0.10)	9.74 (±1.45)	11.05 (±0.12) A	10.80 (±0.21) A	0.03 (±0.03)	0.04 (±0.12)	**0.18** (±0.02)	**0.17** (±0.02)
	10-20	18.35 (±0.12)	16.79 (±1.84)	17.27 (±0.35)	17.43 (±0.43)	0.11 (±0.05)	-0.02 (±0.16)	0.17 (±0.04)	0.08 (±0.07)
	20-40	22.34 (±0.50)	22.66 (±1.18)	19.26 (±0.43)	19.69 (±0.75)	0.19 (±0.18)	0.17 (±0.17)	0.19 (±0.07)	0.18 (±0.13)
	40-60	15.20 (±0.61)	15.86 (±0.55)	13.00 (±0.65)	13.08 (±0.43)	0.14 (±0.18)	0.10 (±0.10)	0.13 (±0.03)	0.17 (±0.06)
	60-80	11.16 (±0.52)	11.95 (±0.62)	9.48 (±0.32)	9.32 (±0.44)	0.04 (±0.14)	0.06 (±0.04)	0.01 (±0.04)	0.04 (±0.06)
	80-100	8.76 (±0.57)	9.37 (±0.82)	7.03 (±0.04)	7.25 (±0.37)	-0.04 (±0.11)	-0.05 (±0.01)	-0.08 (±0.05)	-0.02 (±0.02)
	0-100	95.22 (±2.06)	99.53 (±4.26)	90.23 (±1.52)	91.15 (±1.87)	0.48 (±0.70)	0.65 (±0.58)	0.92 (±0.13)	1.00 (±0.29)
CasEx	0-5	8.44 (±0.23) A	9.48 (±0.09) A	10.68 (±0.00) A	11.67 (±0.34) A	**0.09** (±0.01)	**0.20** (±0.03)	**0.21** (±0.01)	**0.27** (±0.06)
	5-10	8.97 (±0.25) A	9.52 (±0.17) A	9.82 (±0.04) A	9.76 (±0.22) A	**0.05** (±0.01)	**0.16** (±0.02)	**0.10** (±0.00)	**0.12** (±0.03)
	10-20	17.15 (±0.30) A	16.66 (±0.49) A	16.63 (±0.15) A	16.23 (±0.24) A	**0.09** (±0.03)	**0.25** (±0.03)	**0.09** (±0.01)	**0.18** (±0.04)
	20-40	18.18 (±0.94)	18.84 (±0.74) A	20.77 (±0.22) A	19.27 (±1.02) A	-0.09 (±0.11)	**0.22** (±0.06)	**0.29** (±0.06)	**0.29** (±0.01)
	40-60	13.12 (±0.44)	13.42 (±0.36)	13.95 (±0.22)	12.99 (±0.70)	-0.05 (±0.11)	0.14 (±0.05)	0.12 (±0.03)	0.13 (±0.02)
	60-80	11.11 (±0.08)	10.78 (±0.47)	10.61 (±0.49)	10.18 (±0.59)	0.02 (±0.08)	0.09 (±0.04)	-0.01 (±0.01)	0.04 (±0.01)
	80-100	9.47 (±0.09)	8.71 (±0.33)	8.62 (±0.57) B	7.91 (±0.46) B	0.02 (±0.04)	0.01 (±0.01)	**-0.10** (±0.01)	**-0.08** (±0.05)
	0-100	86.44 (±2.12)	87.42 (±2.52) A	91.07 (±0.92) A	88.01 (±3.03) A	0.14 (±0.35)	**1.07** (±0.18)	**0.70** (±0.11)	**0.95** (±0.07)

[a] MaiEx: Maize-based experiment; SoyEx: Soybean-based experiment; and CasEx: Cassava-based experiment.

[b] CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no--till mulch-based cropping systems associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems under NT systems with no-till mulch-based cropping systems associated with different crop sequences as described in Table 1. Different uppercase letters accompanying the values indicate significant difference within the same treatment between 2011 and 2021 (diachronic) at the same soil depth at $p < 0.05$ (Tukey's test). Values of SOC stock change rates in bold indicate changes for a given treatment and depth between 2021 and 2011 are significantly different from 0 at $p <$

0.05 (Tukey’s test). Positive values of SOC stock change rate indicate a SOC accumulation; negative values indicate a SOC loss. Values in the parentheses indicate standard errors (n=3).



~~**3.2** Figure 2. Total N concentration (0-100 cm) in 2011 and 2021 under different cropping systems. CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till associated with different cropping systems as described in Table 1. Treatment(s) in bold within the brackets indicate the gain and~~

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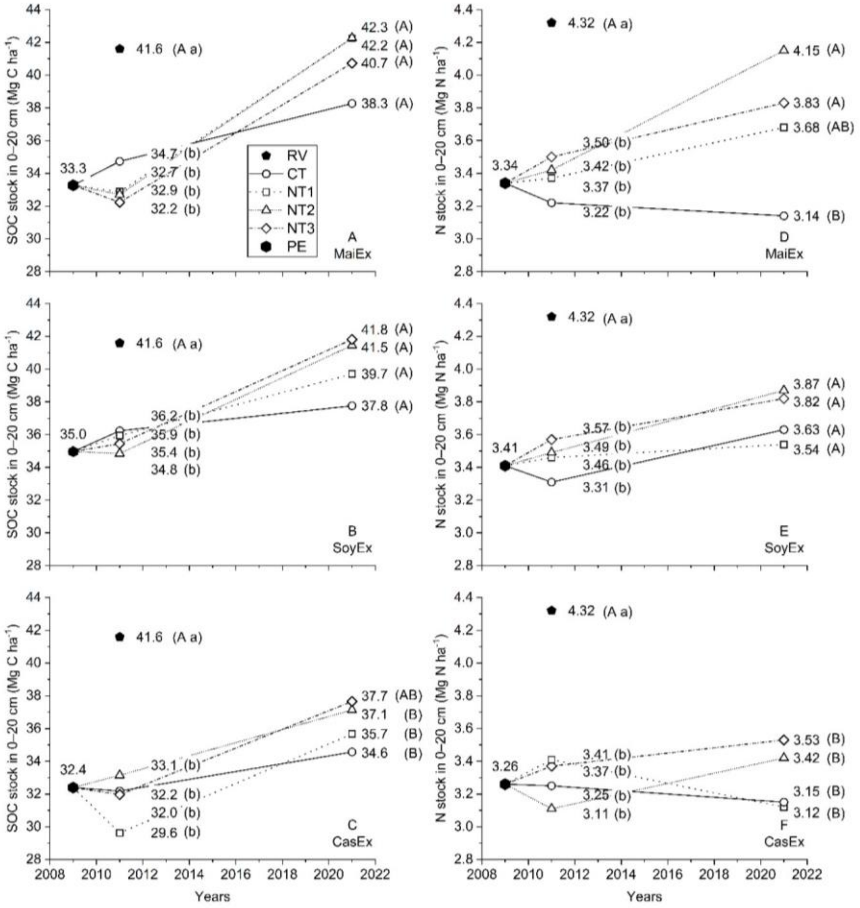

~~significant difference in concentrations between 2011 and 2021 in the same treatment at the same soil depth.~~

~~**Figure 3. Changes in SOC and N stocks (Mg ha-1) at 0–20 cm depth from pre-experiment (PE) in 2009, 2011, and 2021 under different cropping systems with reference vegetation (RV) for comparison. CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till**~~

~~associated with different cropping systems as described in Table 1. Lowercase letters inside the brackets indicate significant difference between RV and the treatment(s) in 2011 and Uppercase letters inside the brackets indicate significant difference between RV and the treatment(s) in 2021 (Tukey's test; P < 0.05).~~

3.2 ~~C~~Impact of ~~tillage and~~ cropping systems on TN concentration and stock~~assava-based experiment~~

~~3.1.3~~3.2.1 Total N concentration

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Over 10 years of cultivation from 2011 to 2021~~a decade~~, ~~all the treatments significantly (P < 0.05) increased SOC concentration in the upper layers (0–10 cm), while significant increases below 10 cm were only observed under NT-Cs systems (Fig. 1F). Among the two treatments of NT-Cs crop rotation systems (NT2-Cs and NT3-Cs), NT3-Cs significantly increased SOC concentration from the top 0 to 60 cm by 30%, 12%, 13%, 23%, and 15% in the 0–5, 5–10, 10–20, 20–40, and 40–60 cm, respectively, while a significant decrease of −13% was recorded in the 80–100 cm depth. Under NT2-Cs, significant increases in SOC concentration were observed up to 40 cm depth with a gain of 24%, 10%, and 23% in 0–5, 5–10, and 20–40 cm, respectively, with a significant decrease by −12% in 80–100 cm depth (Fig. 1E and 1F). In the case of cassava monocropping under NT systems (NT1-Cs), significant increases in SOC concentration were detected from 0 to 80 cm with a gain of 26%, 20%, 19%, 22%, 18%, and 10% in the 0–5, 5–10, 10–20, 20–40, 40–60, and 60–80 cm, respectively (Fig. 1F). For CT-Cs, SOC concentration significantly increased, but at 2 times lower than that of those NT-Cs systems, by 12% and 5% in the top 0–5 and 5–10 cm, respectively, with a significant decrease by −10% detected in 20–40 cm depth (Fig. 1E and 1F).~~

~~From 2011 to 2021, SOC stocks under the NT-Cs crop rotation systems (NT2-Cs and NT3-Cs) increased significantly ($P < 0.05$) by 2.4, 1.1, 1.4, and 2.9 Mg C ha^{-1} in 0–5, 5–10, 10–20, and 20–40 cm,~~

~~respectively, with still a positive trend in 40–60 cm and then a significant decrease by -0.9 Mg C ha^{-1} in 80–100 cm (Table 3). Similarly, NT1-Cs significantly increased SOC stock by 2.0, 1.6, 2.5, and 2.2 Mg C ha^{-1} in 0–5, 5–10, 10–20, and 20–40 cm, respectively (Table 3). For cassava monocropping under conventional tillage (CT-Cs), SOC stock significantly increased, but at 2 times lower than all the NT-Cs systems, by 0.9, 0.5, and 0.9 Mg C ha^{-1} in the 0–5, 5–10, and 10–20 cm, respectively, while no significant changes were recorded below 40 cm (Table 3).~~

~~In 2011, with RV used as a reference (0–20 cm), SOC stock was significantly higher in RV by 23%, 29%, and 22% in CT-Cs, NT1-Cs, and NT-Cs crop rotation systems (average of NT2-Cs and NT3-Cs), respectively. In 2021, the difference in SOC stock with RV declined to 17%, 14%, and 10% in CT-Cs, NT1-Cs, and NT-Cs crop rotation systems, respectively (Fig. 3C).~~

~~Over a 10-year period, from 0 to 100 cm depth, SOC stock significantly increased under all the NT-Cs systems, with an accumulation rate ranging from 0.70 to 1.07 Mg C ha^{-1} yr^{-1}, while the SOC stock change in CT-Cs was not significant and remain stable (Table 3).~~

~~Surprisingly, the response of soil N concentration to tillage systems differed from SOC. NT-Cs crop rotation systems (NT2-Cs and NT3-Cs) significantly increase soil N in the uppermost layer (0–5 cm) with an average increase of 16% (0.28 g N kg^{-1} soil), whereas significant increases were observed by 10% in 5–10 cm and by 19% in 20–40 cm under NT2-Cs (Fig. 2F). Over a 10-year period, cassava monocropping under NT systems (NT1-Cs) resulted in stable N concentration in the top 0–10 cm, but the concentration significantly decreased below 10 cm by -10 to -25% from 10 to 100 cm depth (Fig. 2E). For CT-Cs, N concentration remained stable throughout the soil profile, except a significant loss of -14% detected in the 20–40 cm layer (Fig. 2E).~~

~~In the case of N stock, among the two NT-Cs crop rotation systems (NT2-Cs and NT3-Cs), NT3-Cs significantly increased N stock by 15% (0.1 Mg N ha^{-1}) in the surface 0–5 cm, while significant increases were found by 0.1, 0.1 and 0.3 Mg N ha^{-1} at 0–5, 5–10, and 20–40 cm, respectively, in the NT2-Cs (Table 4). In the case of cassava monocropping, N stock in the NT1-Cs soil remained constant in the top 0–10 cm, then significantly decreased from 10 to 100 cm from -0.3 to -0.5 Mg N ha^{-1}. In a similar trend to NT1-Cs, N stock in CT-Cs soil did not change at the top 0–20 cm, but significantly decreased from -0.2 to -0.3 Mg N ha^{-1} from 20 to 100 cm (Table 4).~~

~~From 2011 to 2021, considering 0–20 cm depth, all tillage and cropping systems did not alter N stocks when compared to RV (Fig. 3F).~~

~~When considering the whole profile (0–100 cm), N stock in the NT-Cs bi-annual rotation systems did not change with time. Regardless of tillage systems, long-term cassava monocropping resulted in significant decreases of N with an annual depletion rate of -0.11 and -0.17 Mg N ha^{-1} yr^{-1} under CT-Cs and NT1-Cs, respectively (Table 4).~~surprisingly, the response of soil TN concentration to tillage and cropping systems differed from SOC (Fig. 2, ~~with~~ Table S4 as duplication~~in the supplementary as the duplication~~). The positive ($p < 0.05$) effect on TN concentration was mainly observed on the surface layer under NT systems. H~~; h~~owever, the significant ($p < 0.05$) decrease in TN concentration varied across tillage, cropping systems and experiments observed below 20 cm (Fig. 2, ~~with~~ Table S4 ~~in the supplementary as the duplication~~). In 2021, NTR systems (NTR1 and NTR2) significantly ($p < 0.05$) increased TN concentration in the top 5 cm of MaiEx (NTR-Mz) and SoyEx (NTR-Sb) by 32% and 23%, respectively (Figs. B2 and 2D), but decreased TN concentration significantly ($p < 0.05$) below 60 to 100 cm by -18 to -21% and -10 to -25% in MaiEx and SoyEX, respectively (Figs. 2A and 2B). Under CasEx in 2021, the soil TN concentration significantly ($p < 0.05$) increased by 16% in the top 0–5 cm under the NTR system (average of NTR1-Cs and NTR2-Cs), while overall TN concentration remained ~~neutral~~stable below 5 cm, except for significant increases under NTR1-Cs by 10% and 19% in the 5–10 cm and 20–40 cm, respectively (Fig. 2F).

From 2011 to 2021, in the case of monocropping under NT systems in MaiEx and SoyEx, the significant ($p < 0.05$) increase in TN concentration by 44% and 25% under NTM-Mz and NTM-Sb, respectively (Figs 2B and 2C). However, the TN concentration was significantly ($p < 0.05$) decreased by -24% in the 40–60 cm under NTM-Mz and from -23 to -29% in the 60–100 cm depth under NTM-Sb (Figs. 2A and 2B). After 10-years of cassava monocropping under NT system (NTM-Cs), TN concentration did not change in the top 0–10 cm, but the concentration significantly ($p < 0.05$) decreased below 10–100 cm depth from -10 to -25% in 2021 (Fig. 2E).

In contrast to NT systems, after 10-years of conventional tillage-based monocropping of soybean (CTM-Sb) and cassava (CTM-Cs), the soil TN concentration in 2021 remained constant across the whole profile, except ~~for~~ a significant ($p < 0.05$) decrease ~~loss~~ of -14% in the 20–40 cm layer detected under CTM-Cs (Fig. 2D and 2E), while in cassava monocropping under CT (CTM-Mz), soil TN concentration remained ~~neutral~~stable from 0 to 40 cm, then significantly ($p < 0.05$) decreased by -12% and -26% in the 40–60 and 80–100 cm depths, respectively (Fig. 2A and 2B).

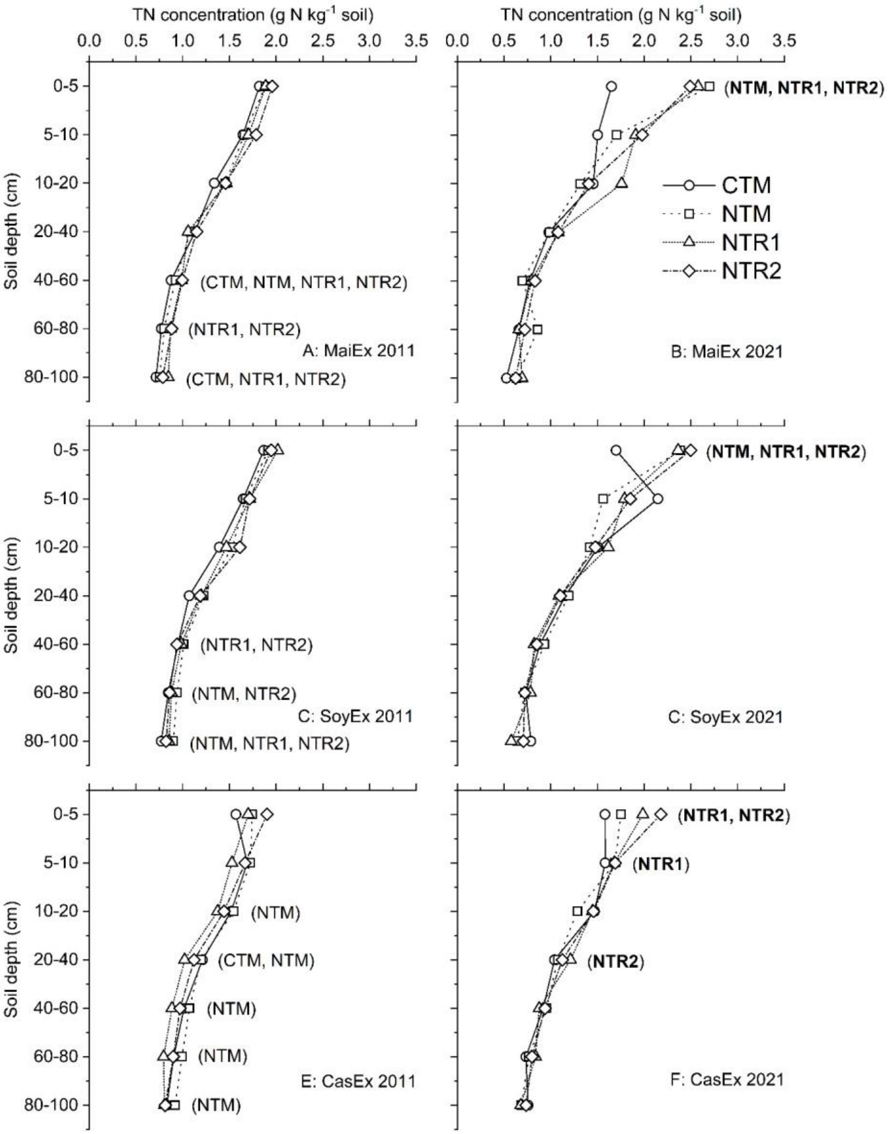

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Figure 2. TN concentration distribution across the soil profile (0–100 cm) of the treatments under different experiments in 2011 and 2021. CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no- till mulch-based cropping systems associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems under NT systems with no-till mulch-based cropping systems associated with different crop sequences as described in Table 1. A: MaiEx 2011 – TN concentration of the treatments in maize-based trial measured in 2011; B: MaiEx 2021 – TN concentration of the treatments in maize-based trial measured in 2021; C: SoyEx 2011 – TN concentration of the treatments in soybean-based trial measured in 2021; D: SoyEx 2021 – TN concentration of the treatments in soybean-based trial measured in 2021; E: CasEx 2011 – TN concentration of the treatments in cassava-based trial measured in 2011; and F: CasEx 2021 – TN concentration of the treatments in cassava-based trial measured in 2021. Treatment(s) in bold within the brackets indicate the gain and significant ($p < 0.05$) difference in concentrations between 2011 and 2021 in the same treatment at the same soil depth.

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3.2.2 Total N stock

Over the past decade, cultivating the main crops (maize, soybean, and cassava) under NTR systems (NTR1 and NTR2) significantly ($p < 0.05$) increased TN stock in the soil surface in all the experiments in 2021. However, the response of TN stock below the surface layers to the NTR systems differed between the three experiments (Table 3, ~~and~~ Table S5~~ in the supplementary~~). In the case of MaiEx (NTR1-Mz and NTR2-Mz), TN stock increased by 0.3 Mg N ha^{-1} in the 0–5 cm; the stock remained ~~neutral~~stable in the 5–40 cm, but then significantly ($p < 0.05$) decreased in the 40–100 cm depths between -0.25 and -0.40 Mg N ha^{-1} (Table 3). Similar to MaiEx, the soil TN stock in the soils under NTR systems of SoyEx (NTR1-Sb and NTR2-Sb) significantly increased by 0.25 Mg N ha^{-1} in the 0–5 cm layer, remained constant in the 5–60 cm, and then significantly decreased in the 60–100 cm with a rough amount of -0.02 Mg N ha^{-1} (Table 3). In contrast to MaiEx and SoyEx, among the two NTR-Cs crop rotation system, NTR2-Cs significantly ($p < 0.05$) increased TN stock by 0.10 Mg N ha^{-1} in the surface 0–5 cm, whereas the significant increase in TN stock was detected in the 0–5, 5–10 and 20–40 cm by 0.10, 0.10 and 0.03 Mg

N ha^{-1}, respectively, under NTR1-Cs. Unlike, MaiEx and SoyEx, there was no significant decrease in TN stock in the subsoil layers under the NTR-Cs (Table 3).

When compared to 2011, TN stock in 2021 of MaiEx and SoyEx under the NTM system significantly (p <0.05) increased in the topsoil (0–5 cm) by 0.40 and 0.20 Mg N ha^{-1} under NTM-Mz and NTM-Sb, respectively. However, significant ($p < 0.05$) decreases in TN stock were detected in the subsoils under NTM-Mz by -0.40 Mg N ha^{-1} in the 40–60 cm and by -0.30 to -0.40 Mg N ha^{-1} in the 60–100 cm under NTM-Sb (Table 3). In the case of CasEx, TN stock in the NTM-Cs soil remained constant in the top 0–10 cm, then significantly decreased from -0.3 to -0.5 Mg N ha^{-1} in the 10–100 cm (Table 3).

For the CTM of all the experiments, from 2011 to 2021, TN stock in the topsoil layers remained stable, whereas losses were observed in the layers below 20 cm. CTM-Sb significantly ($p < 0.05$) increased TN stock by 0.20 Mg N ha^{-1} in the 10–20 cm, then remained constant below 20 cm with a significant ($p <$ 0.05) reduction by -0.20 Mg N ha^{-1} detected in the 60–80 cm (Table 3). In CTM-Mz, TN stock did not change in the 0–40 cm but significantly declined between -0.20 to -0.30 Mg N ha^{-1} from 40–100 cm (Table 3). In CTM-Cs soil, TN stock did not change in the top 0–20 cm but significantly decreased from -0.20 to -0.30 Mg N ha^{-1} in the 20–100 cm (Table 3).

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Measured in the whole profile (0–100 cm), over the past decade, the TN stock under NTR systems of all the experiments remained ~~neutral~~stable (Table 3). Monocropping of soybean and cassava under NT systems (NTM-Sb and NTM-Cs) caused a significant ($p < 0.05$) reduction of TN stock at the annual depletion rate of -0.10 and -0.17 Mg N ha^{-1} yr^{-1}, respectively, while nearly a decade of upland rice monocropping then recent shift~~ed~~ to maize under NTM system (NTM-Mz) did not change TN stock (Table 3). In the case of monocropping of main crops under CT, the TN stock under CTM-Cs

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~~**Table 3**. Mean SOC stocks in 2021 and SOC stock change rate between 2021 and 2011.~~

~~**Experiments[a]**~~	~~**Approximate soil depth (cm)**~~	~~**Cropping systems[b]**~~							
		~~**CT**~~	~~**NT1**~~	~~**NT2**~~	~~**NT3**~~	~~**CT**~~	~~**NT1**~~	~~**NT2**~~	~~**NT3**~~
		~~**SOC stock in 2021 (Mg C ha^{-1})**~~				~~**SOC stock change rate 2021-11 (Mg C ha^{-1} yr^{-1})**~~			
~~MaiEx~~	~~0-5~~	~~9.83 c~~	~~15.01 Aa~~	~~14.03 Aab~~	~~13.52 Ab~~	~~0.04~~	~~**0.61**~~	~~**0.48**~~	~~**0.44**~~
	~~5-10~~	~~10.16 Ab~~	~~10.91 Aab~~	~~11.16 Aa~~	~~10.89 Aab~~	~~**0.09**~~	~~**0.22**~~	~~**0.23**~~	~~**0.22**~~
	~~10-20~~	~~18.28 A~~	~~16.31~~	~~17.08 A~~	~~16.32 A~~	~~**0.23**~~	~~0.11~~	~~**0.25**~~	~~**0.19**~~
	~~20-40~~	~~19.90~~	~~18.61~~	~~20.28 A~~	~~18.64~~	~~0.11~~	~~0.16~~	~~**0.45**~~	~~0.07~~
	~~40-60~~	~~12.58~~	~~12.18~~	~~12.75~~	~~12.31~~	~~-0.04~~	~~0.08~~	~~0.10~~	~~0.02~~
	~~60-80~~	~~9.01 B~~	~~9.58~~	~~9.64~~	~~9.33~~	~~**-0.12**~~	~~0.07~~	~~-0.02~~	~~-0.02~~
	~~80-100~~	~~7.17 B~~	~~7.51~~	~~7.97~~	~~7.26~~	~~**-0.13**~~	~~0.05~~	~~-0.02~~	~~-0.06~~
	~~0-100~~	~~86.92~~	~~90.13 A~~	~~92.90 A~~	~~88.27 A~~	~~0.17~~	~~**1.30**~~	~~**1.47**~~	~~**0.86**~~
~~SoyEx~~	~~0-5~~	~~9.45 b~~	~~13.17 Aa~~	~~13.14 Aa~~	~~13.58 Aa~~	~~0.02~~	~~**0.36**~~	~~**0.32**~~	~~**0.39**~~
	~~5-10~~	~~9.95~~	~~9.74~~	~~11.05 A~~	~~10.80 A~~	~~0.03~~	~~0.04~~	~~**0.18**~~	~~**0.17**~~
	~~10-20~~	~~18.35~~	~~16.79~~	~~17.27~~	~~17.43~~	~~0.11~~	~~-0.02~~	~~0.17~~	~~0.08~~
	~~20-40~~	~~22.34~~	~~22.66~~	~~19.26~~	~~19.69~~	~~0.19~~	~~0.17~~	~~0.19~~	~~0.18~~
	~~40-60~~	~~15.20~~	~~15.86~~	~~13.00~~	~~13.08~~	~~0.14~~	~~0.10~~	~~0.13~~	~~0.17~~
	~~60-80~~	~~11.16~~	~~11.95~~	~~9.48~~	~~9.32~~	~~0.04~~	~~0.06~~	~~0.01~~	~~0.04~~
	~~80-100~~	~~8.76~~	~~9.37~~	~~7.03~~	~~7.25~~	~~-0.04~~	~~-0.05~~	~~-0.08~~	~~-0.02~~
	~~0-100~~	~~95.22~~	~~99.53~~	~~90.23~~	~~91.15~~	~~0.48~~	~~0.65~~	~~0.92~~	~~1.00~~
~~CasEx~~	~~0-5~~	~~8.44 Ac~~	~~9.48 Ab~~	~~10.68 Aa~~	~~11.67 Aa~~	~~**0.09**~~	~~**0.20**~~	~~**0.21**~~	~~**0.27**~~
	~~5-10~~	~~8.97 Ab~~	~~9.52 Aab~~	~~9.82 Aa~~	~~9.76 Aa~~	~~**0.05**~~	~~**0.16**~~	~~**0.10**~~	~~**0.12**~~
	~~10-20~~	~~17.15 A~~	~~16.66 A~~	~~16.63 A~~	~~16.23 A~~	~~**0.09**~~	~~**0.25**~~	~~**0.09**~~	~~**0.18**~~
	~~20-40~~	~~18.18~~	~~18.84 A~~	~~20.77 A~~	~~19.27 A~~	~~-0.09~~	~~**0.22**~~	~~**0.29**~~	~~**0.29**~~
	~~40-60~~	~~13.12~~	~~13.42~~	~~13.95~~	~~12.99~~	~~-0.05~~	~~0.14~~	~~0.12~~	~~0.13~~
	~~60-80~~	~~11.11~~	~~10.78~~	~~10.61~~	~~10.18~~	~~0.02~~	~~0.09~~	~~-0.01~~	~~0.04~~
	~~80-100~~	~~9.47~~	~~8.71~~	~~8.62 B~~	~~7.91 B~~	~~0.02~~	~~0.01~~	~~**-0.10**~~	~~**-0.08**~~
	~~0-100~~	~~86.44~~	~~87.42 A~~	~~91.07 A~~	~~88.01 A~~	~~0.14~~	~~**1.07**~~	~~**0.70**~~	~~**0.95**~~

~~[a] MaiEx: Maize-based experiment; SoyEx: Soybean-based experiment; and CasEx: Cassava-based experiment.~~

~~[b] CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till associated with cropping systems as described in Table 1. Different uppercase letters accompanying the values indicate significant difference within the same treatment between 2011 and 2021 (diachronic), and different lowercase letters indicate significant difference between the treatments within the same sampling date (synchronic) at the same soil depth at P ≤ 0.05 (Tukey's test). Values of SOC stock change rates in bold indicate changes for a given treatment and depth between 2021 and 2011 are significantly different from 0 at~~

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~~P ≤ 0.05 (Tukey's test). Positive values of SOC stock change rate indicate a SOC accumulation; negative values indicate a SOC loss.~~

Table 3~~4~~. Mean T~~total~~ N stock in 2021 and TN stock change rate between 2021 and 2011.

Experiments[a]	Approximate soil depth (cm)	Cropping systems[b]							
		CTM	**NTM~~1~~**	**NTR1~~2~~**	**NTR2~~3~~**	**CTM**	**NTM~~1~~**	**NTR1~~2~~**	**NTR2~~3~~**
		N stock in 2021 (Mg N ha^{-1})				**N stock change rate 2021-11 (Mg N ha^{-1} yr^{-1})**			
MaiEx ~~MaiEx~~	0-5 ~~0-5~~	0.79 (±0.04) ~~0.79~~ ~~b~~	1.30 (±0.02) ~~1.30~~ A ~~A~~ ~~a~~	1.24 (±0.03) ~~1.24~~ A ~~A~~ ~~a~~	1.20 (±0.04) ~~1.20~~ A ~~A~~ ~~a~~	-0.01 (±0.01) ~~-0.01~~	**0.04** (±0.01) **0.04**	**0.03** (±0.00) **0.03**	**0.03** (±0.00) **0.03**
	5-10 ~~5-10~~	0.79 (±0.05) ~~0.79~~ ~~b~~	0.95 (±0.01) ~~0.95~~ A ~~a~~ ~~b~~	1.04 (±0.02) ~~1.04~~ ~~a~~	1.06 (±0.12) ~~1.06~~ ~~a~~	-0.01 (±0.01) ~~-0.01~~	0.01 (±0.00) ~~0.01~~	0.01 (±0.00) ~~0.01~~	0.01 (±0.01) ~~0.01~~
	10-20 ~~10-20~~	1.55 (±0.01) ~~1.55~~ ~~a~~ ~~b~~	1.44 (±0.03) ~~1.44~~ B ~~b~~	1.87 (±0.23) ~~1.87~~ ~~a~~	1.58 (±0.12) ~~1.58~~ ~~a~~ ~~b~~	0.01 (±0.01) ~~0.01~~	-0.01 (±0.01) ~~-0.01~~	0.03 (±0.02) ~~0.03~~	0.00 (±0.02) ~~0.00~~
	20-40 ~~20-40~~	1.98 (±0.10) ~~1.98~~	1.91 (±0.06) ~~1.91~~	2.18 (±0.11) ~~2.18~~	2.11 (±0.05) ~~2.11~~	-0.02 (±0.02) ~~-0.02~~	-0.02 (±0.00) ~~-0.02~~	0.01 (±0.02) ~~0.01~~	-0.02 (±0.01) ~~-0.02~~
	40-60 ~~40-60~~	1.46 (±0.03) ~~1.46~~ B ~~B~~	1.33 (±0.11) ~~1.33~~ B ~~B~~	1.48 (±0.12) ~~1.48~~ B ~~B~~	1.56 (±0.05) ~~1.56~~ B ~~B~~	**-0.02** (±0.01) ~~**-0.02**~~	**-0.04** (±0.00) ~~**-0.04**~~	**-0.03** (±0.01) ~~**-0.03**~~	**-0.03** (±0.01) ~~**-0.03**~~
	60-80 ~~60-80~~	1.24 (±0.09) ~~1.24~~ B ~~B~~	1.49 (±0.13) ~~1.49~~	1.25 (±0.04) ~~1.25~~ B ~~B~~	1.36 (±0.02) ~~1.36~~ B ~~B~~	**-0.02** (±0.01) ~~**-0.02**~~	-0.01 (±0.01) ~~-0.01~~	**-0.04** (±0.01) ~~**-0.04**~~	**-0.04** (±0.00) ~~**-0.04**~~
	80-100 ~~80-100~~	1.00 (±0.08) ~~1.00~~ B ~~B~~	1.22 (±0.02) ~~1.22~~	1.21 (±0.03) ~~1.21~~ B ~~B~~	1.17 (±0.03) ~~1.17~~ B ~~B~~	**-0.03** (±0.01) ~~**-0.03**~~	-0.02 (±0.01) ~~-0.02~~	**-0.03** (±0.01) ~~**-0.03**~~	**-0.04** (±0.00) ~~**-0.04**~~
	0-100 ~~0-100~~	8.82 (±0.46) ~~8.82~~	9.63 (±0.49) ~~9.63~~	10.27 (±0.17) ~~10.27~~	10.03 (±0.30) ~~10.03~~	-0.11 (±0.02) ~~-0.11~~	-0.06 (±0.06) ~~-0.06~~	-0.03 (±0.06) ~~-0.03~~	-0.09 (±0.03) ~~-0.09~~
SoyEx ~~SoyEx~~	0-5 ~~0-5~~	0.82 (±0.03) ~~0.82~~ ~~b~~	1.15 (±0.01) ~~1.15~~ A ~~A~~ ~~a~~	1.13 (±0.03) ~~1.13~~ A ~~A~~ ~~a~~	1.20 (±0.06) ~~1.20~~ A ~~A~~ ~~a~~	-0.01 (±0.00) ~~-0.01~~	**0.02** (±0.00) **0.02**	**0.02** (±0.00) **0.02**	**0.03** (±0.01) **0.03**
	5-10 ~~5-10~~	1.07 (±0.22) ~~1.07~~	0.87 (±0.11) ~~0.87~~	0.99 (±0.02) ~~0.99~~	1.00 (±0.03) ~~1.00~~	0.02 (±0.02) ~~0.02~~	0.00 (±0.01) ~~0.00~~	0.01 (±0.00) ~~0.01~~	0.01 (±0.00) ~~0.01~~
	10-20 ~~10-20~~	1.75 (±0.12) ~~1.75~~ A ~~A~~	1.53 (±0.08) ~~1.53~~	1.74 (±0.09) ~~1.74~~	1.62 (±0.02) ~~1.62~~	**0.02** (±0.01) **0.02**	-0.01 (±0.00) ~~-0.01~~	0.01 (±0.01) ~~0.01~~	-0.01 (±0.01) ~~-0.01~~
	20-40 ~~20-40~~	2.28 (±0.04) ~~2.28~~	2.29 (±0.12) ~~2.29~~	2.20 (±0.06) ~~2.20~~	2.14 (±0.04) ~~2.14~~	0.02 (±0.01) ~~0.02~~	-0.01 (±0.01) ~~-0.01~~	-0.01 (±0.02) ~~-0.01~~	-0.02 (±0.02) ~~-0.02~~

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	40-60~~40-60~~	1.74 (±0.04)~~1.74~~		1.80 (±0.05)~~1.80~~	A ~~A~~	1.60 (±0.09) ~~1.60~~		1.62 (±0.03)~~1.62~~		0.00 (±0.01)~~0.00~~	-0.02 (±0.01)~~-0.02~~	-0.03 (±0.02)~~-0.03~~	-0.02 (±0.01)~~-0.02~~
	60-80~~60-80~~	1.44 (±0.05)~~1.44~~	B ~~B~~	1.47 (±0.08)~~1.47~~	B ~~B~~	1.44 (±0.03)~~1.44~~	B ~~B~~	1.39 (±0.02)~~1.39~~	B ~~B~~	**-0.02** (±0.00)~~**-0.02**~~	**-0.03** (±0.01)~~**-0.03**~~	**-0.02** (±0.01)~~**-0.02**~~	**-0.02** (±0.01)~~**-0.02**~~
	80-100~~80-100~~	1.36 (±0.04)~~1.36~~		1.21 (±0.17)~~1.21~~	B ~~B~~	1.18 (±0.04) ~~1.18~~	B ~~B~~	1.26 (±0.01) ~~1.26~~	B ~~B~~	-0.01 (±0.00)~~-0.01~~	**-0.04** (±0.02)~~**-0.04**~~	**-0.04** (±0.01)~~**-0.04**~~	**-0.02** (±0.00)~~**-0.02**~~
	0-100~~0-100~~	10.45 (±0.39)~~10.45~~		10.31 (±0.29)~~10.31~~	B ~~B~~	10.29 (±0.13) ~~10.29~~		10.23 (±0.12) ~~10.23~~		0.02 (±0.04)~~0.02~~	**-0.10** (±0.03)~~**-0.10**~~	-0.06 (±0.03)~~-0.06~~	-0.06 (±0.03)~~-0.06~~
CasEx~~CasEx~~	0-5~~0-5~~	0.76 (±0.01)~~0.76~~	~~c~~	0.84 (±0.01)~~0.84~~	~~b c~~	0.95 (±0.01) ~~0.95~~	A ~~A a b~~	1.05 (±0.04) ~~1.05~~	A ~~A a~~	0.00 (±0.00)~~0.00~~	0.00 (±0.00)~~0.00~~	**0.01** (±0.00)~~**0.01**~~	**0.01** (±0.01)~~**0.01**~~
	5-10~~5-10~~	0.82 (±0.02)~~0.82~~		0.88 (±0.01)~~0.88~~		0.89 (±0.02) ~~0.89~~	A ~~A~~	0.91 (±0.01)~~0.91~~		0.00 (±0.00)~~0.00~~	0.00 (±0.00)~~0.00~~	**0.01** (±0.00)~~**0.01**~~	0.00 (±0.00)~~0.00~~
	10-20~~10-20~~	1.57 (±0.03)~~1.57~~	~~a b~~	1.40 (±0.07)~~1.40~~	B ~~B b~~	1.57 (±0.02) ~~1.57~~	A ~~a b~~	1.58 (±0.01)~~1.58~~	A ~~a~~	-0.01 (±0.01)~~-0.01~~	**-0.03** (±0.01)~~**-0.03**~~	0.01 (±0.00)~~0.01~~	0.00 (±0.00)~~0.00~~
	20-40~~20-40~~	2.06 (±0.07)~~2.06~~	B ~~B~~	2.04 (±0.10)~~2.04~~	B ~~B~~	2.34 (±0.02)~~2.34~~	A ~~A~~	2.19 (±0.10)~~2.19~~		**-0.03** (±0.01)~~**-0.03**~~	**-0.03** (±0.01)~~**-0.03**~~	**0.03** (±0.00)~~**0.03**~~	0.00 (±0.01)~~0.00~~
	40-60~~40-60~~	1.69 (±0.05)~~1.69~~	B ~~B~~	1.74 (±0.05)~~1.74~~	B ~~B~~	1.75 (±0.03) ~~1.75~~		1.74 (±0.06)~~1.74~~		**-0.02** (±0.01)~~**-0.02**~~	**-0.03** (±0.00)~~**-0.03**~~	0.01 (±0.00)~~0.01~~	-0.01 (±0.01)~~-0.01~~
	60-80~~60-80~~	1.48 (±0.10)~~1.48~~	B ~~B~~	1.51 (±0.11)~~1.51~~	B ~~B~~	1.54 (±0.02) ~~1.54~~		1.52 (±0.02) ~~1.52~~		**-0.02** (±0.02)~~**-0.02**~~	**-0.04** (±0.01)~~**-0.04**~~	0.00 (±0.00)~~0.00~~	-0.02 (±0.01)~~-0.02~~
	80-100~~80-100~~	1.32 (±0.09)~~1.32~~		1.29 (±0.11)~~1.29~~	B ~~B~~	1.34 (±0.05) ~~1.34~~		1.35 (±0.03) ~~1.35~~		-0.02 (±0.01)~~-0.02~~	**-0.05** (±0.01)~~**-0.05**~~	-0.01 (±0.01)~~-0.01~~	-0.02 (±0.01)~~-0.02~~
-	0-100~~0-100~~	9.70 (±0.21)~~9.70~~	B ~~B~~	9.70 (±0.39)~~9.70~~	B ~~B~~	10.40 (±0.04) ~~10.40~~		10.34 (±0.25) ~~10.34~~		**-0.11** (±0.06)~~**-0.11**~~	**-0.17** (±0.07)~~**-0.17**~~	0.06 (±0.02)~~0.06~~	-0.03 (±0.01)~~-0.03~~

[a] MaiEx: Maize-based experiment; SoyEx: Soybean-based experiment; and CasEx: Cassava-based experiment.

[b] CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no-–till mulch-based cropping systems associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems under NT systems with no-till mulch-based cropping systems ~~NT: no-till, NT1, NT2, and NT3 refer to no-till~~ associated with cropping systems as described in Table 1. Different uppercase letters accompanying the values indicate significant difference within the same treatment between 2011 and 2021 (diachronic)~~, and different lowercase letters indicate significant difference between the treatments within the same sampling date (synchronic)~~ at the same soil depth at *p*~~P~~ ≤~~≤~~

0.05 (Tukey's test). Values of TN stock change rates in bold indicate changes for a given treatment and depth between 2021 and 2011 are significantly different from 0 at $p <$ ~~$P \leq$~~ 0.05 (Tukey's test). Positive values of TN stock change rate indicate a N accumulation; negative values indicate a N loss. Values in the parentheses indicate standard errors (n=3).

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3.3 ~~The i~~Impacts of ~~tillage and~~ cropping systems on ~~organic~~ C and N ~~concen~~stoc~~ration~~ks in size fractions

3.3.1 C stock in size fractions

In this diachronic study, over the 10-year period, the stocks of C-POM and C-MAOM were significantly ($p < 0.05$) influenced by all the treatments. H~~; h~~owever, the effects varied across cropping systems and the experiments (Fig. 4,~~ with~~ Table S6 and S7~~ in the supplementary as duplications~~).

The data showed that C-POM stock in 2021 significantly ($p < 0.05$) increased in the surface layers (0–10 cm) under all the NT systems in MaiEx and SoyEx, but it was not the case in CasEx (Figs. 4B, 4D, and 4F). The annual accumulation rates of C-POM stock in MaiEx and SoyEx were similar, with a range~~d~~ of approximately 0.15 and 0.04 Mg C ha^{-1} yr^{-1} under NTM system and 0.10 and 0.03 Mg C ha^{-1} yr^{-1} under NTR systems (average of NTR1 and NTR2) in the 0–5 and 5–10 cm, respectively. This suggested the consequence of the annual biomass inputs that were left on the soil surface under all the NT systems over the experimental period (Table 1). Although the significant increase in C-POM stock was also detected under CTM in the tilled layers (5–20 cm) in MaiEx and SoyEx, at the annual accumulation rates of only 0.02 Mg C ha^{-1} yr^{-1} across the two soil depths (5–10 and 10–20 cm), which is relatively low when compared with NT systems (Figs. 4B and 4D).

In a similar trend to C-POM, C-MAOM stock increased significantly ($p < 0.05$) in the top soil depths under all the NT systems in MaiEx and SoyEx in 2021. The annual accumulation rates were similar between NTM-Mz and NTR-Mz, with a rate of 0.33 and 0.15 Mg C ha^{-1} yr^{-1} in the 0–5 and 5–10 cm, respectively (Fig. 4B). In SoyEx, all the NT systems exhibited the trend of C-MAOM stock accumulation in the deeper layers (to 20 cm) than MaiEx, with approximate annual accumulation rates of 0.20, 0.15,

Formatted: Font: Italic, Complex Script Font: Italic and 0.10 Mg C ha^{-1} yr^{-1} in the 0–5, 5–10, and 10–20 cm, respectively (Fig. 4D). In CasEx, despite the fact that the C-POM stock remained constant over the past decade, the C-MAOC stock significantly ($p < 0.05$) increased down to 40 cm by all the NT systems in 2021, with similar accumulation rates from 0.09 to 0.26 Mg C h^{-1} yr^{-1} in the 0–40 cm depths (Fig 4F).

~~3.5~~ Under CTM in 2021, an increase in C-MAOM stock was observed in the tilled layers across all experiments (Figs. 4B, 4D, and 4F). Specifically, in the MaiEx experiment, significant differences ($p <$ 0.05) of C-MAOM stock between 2011 and 2021 were found in the 5–10 cm and 10–20 cm layers, with annual accumulation rates of 0.10 and 0.23 Mg C ha^{-1} yr^{-1}, respectively (Fig. 4B). In the case of SoyEx, a significant increase in C-MAOM stock was only detected in the 10–20 cm layer, with an annual accumulation rate of 0.11 Mg C ha^{-1} yr^{-1} (Fig. 4D). Meanwhile, in the CasEx experiment, the C-MAOM stock showed a significant annual increase at a rate of 0.05 Mg C ha^{-1} yr^{-1} across the topsoil 0–20 cm (Fig. 4F).

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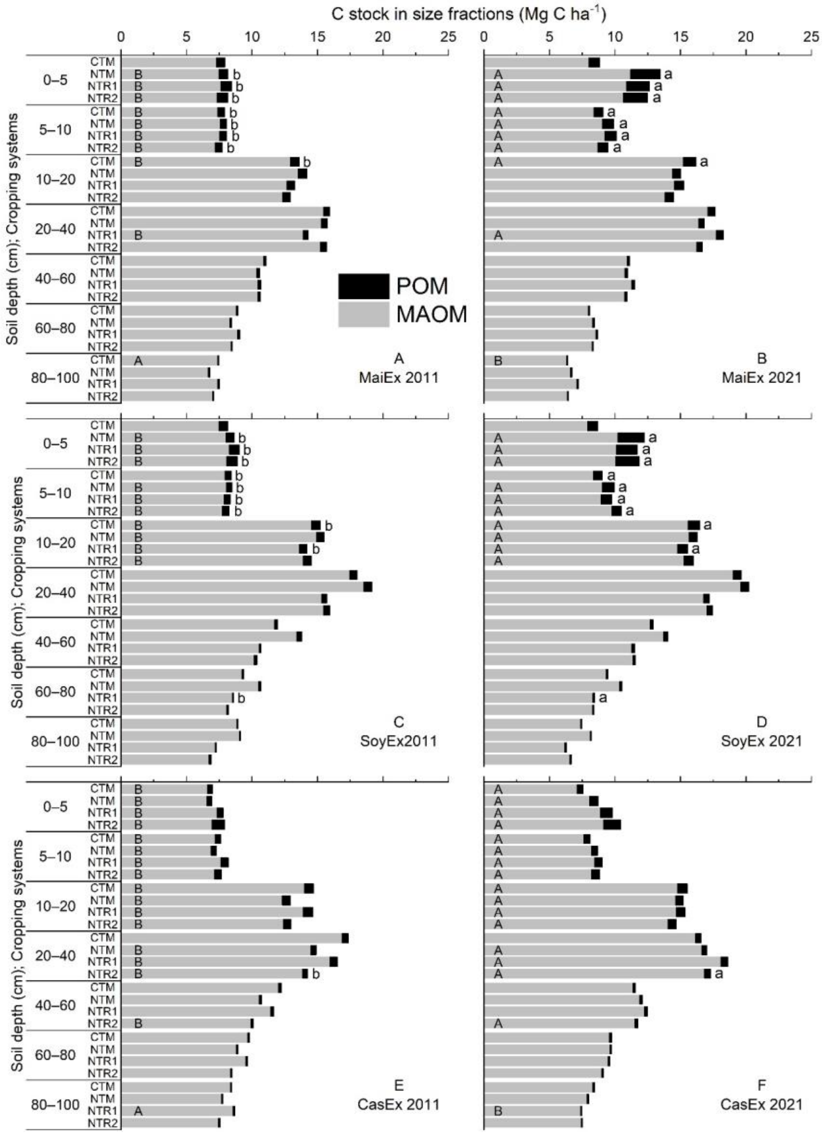

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~~Fig. 4 (with duplicates of Table S5 and S6 in supplementary materials) shows the depth distribution and the proportion of C in POM (C-POM) and MAOM (C-MAOM) concentrations in 2011 and 2021, while the depth distribution and the proportion of N concentrations in the POM (N-POM) and MAOM (N-MAOM) fractions in 2011 and 2021 are presented in Fig. 5 (with the duplicates in Table S7 and S8 in the supplementary materials).~~

3.2

~~3.5.1 Maize-based experiment~~

~~Over the 10-year period, the concentrations of C-POM and C-MAOM were significantly ($P < 0.05$) influenced by all the treatments; however, the effects varied across cropping systems (Fig. 4A and 4B). Among the two treatments of NT-Mz crop rotation systems (NT2-Mz and NT3-Mz), NT3-Mz significantly increased C-POM by 126% in 0–5 cm and C-MAOM by 45% and 19% in 0–5, and 5–10 cm, respectively. NT2-Mz significantly increased C-POM by 117%, 48%, and 68% and C-MAOM by 43%, 21%, and 37% in the 0–5, 5–10, and 20–40 cm, respectively (Fig. 4A and 4B). For NT1-Mz, significant increases were found in C-POM by 226% and 59% in 0–5 and 5–10 cm depths, respectively. C-MAOM concentration was also significantly increased under NT1-Mz by 50%, 17%, 14%, and 12% in 0–5, 5–10, 20–40, and 40–60 cm, respectively (Fig. 4A and 4B). Significant increases in C-POM by 44% and 52% and C-MAOM by 14% and 19% in the 5–10 and 10–20 cm, respectively, were observed in CT-Mz soil (Fig. 4A and 4B). At 80–100 cm depth, a significant decrease in C-MAOM by -11%, was observed under CT-Mz, while this was not the case for all the NT-Mz systems (Fig. 4A and 4B).~~

~~Adoption of all the NT-Mz systems significantly ($P < 0.05$) increased N-POM concentration in the surface layers (0–10 cm), while significant decreases were observed below 40 cm (Fig. 5A and 5B). The concentration of N-POM under NT3-Mz significantly increased by 151% in 0–5 cm, but significantly decreased by -41% in 40–60 cm layer. NT2-Mz significantly increased N-POM by 142% and 77% in 0–5 and 5–10 cm, respectively, whereas the concentration was significantly reduced by -42% to -76% from 40 to 100 cm depths (Fig. 5A and 5B). The N-POM concentration was significantly increased in NT1-Mz by 258% and 61% in the top 0–5 and 5–10 cm, respectively, but was significantly reduced by -26% and -71% in 40–60 and 80–100 cm depth, respectively. N-POM under CT-Mz did not change in the surface soils but significantly decreased by -59% to -77% from 40 to 100 cm (Fig. 5A and 5B). Our diachronic study showed that adopting crop rotations under NT-Mz systems did not enhance N-MOAM at any soil depth but resulted in significant ($P < 0.05$) N loss in MAOM below 5 cm in NT2-Mz and below 20 cm in NT3-Mz (Fig. 5A and 5B). For rice monocropping for nearly a decade and the shift to recent maize monocropping under both conventional tillage and NT systems, the concentration of N-MAOM remained stable throughout the whole profile, with the exception of significant ($P < 0.05$) decreases found in 40–60 and 80–100 cm depths under CT-Mz and NT1-Mz, respectively (Fig. 5A and 5B).~~

~~3.5.1 Soybean-based experiment~~

~~Under this diachronic analysis, the concentration of C and N in the POM fraction showed similar patterns and magnitudes as in MaiEx (Fig. 4 and 5). C-POM in the top 0–20 cm was influenced by~~

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~~tillage and cropping systems. Adoption of NT-Sb crop rotation systems (NT2-Sb and NT3-Sb) significantly (P < 0.05) increased C-POM by 115% and 47% in 0–5 and 5–10 cm, respectively (Fig. 4D). Under NT1-Sb, C-POM significantly increased by 215%, 101% and 72% in 0–5, 5–10, and 10–20 cm, respectively. The amount of C-POM in CT-Sb soil significantly increased in the ploughed layers (5–10 and 10–20 cm) but at approximately 2 times lower than those NT-Sb systems (Fig. 4D). The C-POM concentration did not change below 20 cm in all the treatments, with the exception of a significant decrease under NT3-Sb in 80–100 cm (Fig. 4C and 4D). The effects of cropping systems on C-MAOM concentration varied across the four treatments and soil depths (Fig. 4C and 4D). Compared between the two treatments in NT-Sb crop rotation systems, NT3-Sb significantly (P < 0.05) enhanced C-MAOM by 25%, 29%, 7%, and 13% in 0–5, 5–10, 10–20, 40–60 cm depth, respectively. In the case of NT2-Sb, C-MAOM significantly increased by 22% and 8% in 0–5, and 10–20 cm, respectively, with a significant reduction by -19% in the lowest profile (80–100 cm). Similar to NT2-Sb, NT1-Sb significantly increased C-MAOM by 28% and 5% in 0–5 and 10–20 cm, respectively, with a significant decline by -16% detected in the lowest profile (80–100 cm). For CT-Sb, significant increases in C-MAOM were observed by 7% and 12% in 10–20 and 40–60 cm depth, respectively, with a significant decrease by -13% spotted in 80–100 cm depth (Fig. 4C and 4D).~~

~~From 2011 to 2021, the amount of N-POM fraction under NT-Sb crop rotation systems significantly (P < 0.05) increased by an average of 0.13 g N kg-1 soil at 0–5 cm and 0.02 g N kg-1 soil at 5–10 cm. Significant decrease of N-POM below 60 cm was found in NT3-Sb, but it was not the case in NT2-Sb (Fig. 5D). NT1-Sb significantly increased N-POM by 0.21, 0.05, and 0.02 g N kg-1 soil in 0–5, 5–10, and 10–20 cm, respectively, while the concentration remained constant below 20 cm. Under CT-Sb, N-POM significantly increased at the same amount of 0.02 g N kg-1 soil in the plough layers (5–10 and 10–20 cm), with a significant decrease found in 80–100 cm (Fig. 5C and 5D).~~

~~In contrast to C-POM, the amount of N- MAOM in all the NT-Sb systems did not change from 0 to 40 cm, but significant reductions were observed below 40 cm. NT2-Sb significant loss N- MAOM by -43% to -61% from 60 to 100 cm, whereas a significant loss of 40% at 80–100 cm was observed in NT3-Sb (Fig. 5C and 5D). Under long-term soybean monocropping, the concentration of N-MAOM significantly decreased by -25% to -49% and -33% to -58% from 60–100 cm under NT1-Sb and CT-Sb, respectively (Fig. 5C and 5D).~~

~~3.5.2 Cassava-based experiment~~

~~After 10 years of experimentation, all the treatments in CasEx had no significant effect on the C-POM concentration in the topsoil (0–20 cm) as observed in MaiEx and SoyEx (Fig. 4E and 4F). Except for a few significant increases in C-POM detected under NT1-Cs and NT3-Sb in 20–40 cm and significant decreases in C-POM under CT-Cs and NT2-Cs in 20–40 and 60–80 cm, respectively, the C-POM concentration in all treatments remained constant below 20 cm (Fig. 4E and 4F). Surprisingly, all the treatments had a significant positive impact on C-MAOM in the upper 0–20 cm, and the effects even extended below 20 cm under all the NT-Cs systems (Fig. 4E and 4F). The concentration of C-MAOM significantly increased under NT-Cs crop rotation systems (average of NT2-Cs and NT3-Cs) by 26%, 11%, 9%, 24%, and 13% in 0–5, 5–10, 10–20, 20–40, and 40–60 cm, respectively. NT1-Cs significantly enhanced C-MAOM by at least 11% to 23% from 0 to 80 cm~~

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~~**(Fig. 4E). The concentration of C-MAOM was significantly increased under CT-Cs at roughly 6% in the top 0–20 cm, and the concentration did not change below 20 cm (Fig. 4E and 4F).**~~

~~**Over a 10-year period, the concentration of N-POM was not influenced by any treatments, while all the treatments significantly reduced the N-MAOM concentration across the soil profile (Fig. 5E and 5F). Despite the fact that the N-MAOM did not change in the top 0–5 cm, the concentration significantly decreased by -14% to -69% from 5 to 100 cm across all three NT-Cs systems. For CT-Cs, N-MAOM concentration significantly decreased in the whole profile (0–100 cm) with a depletion of -20% to -52% (Fig. 5E and 5F).**~~

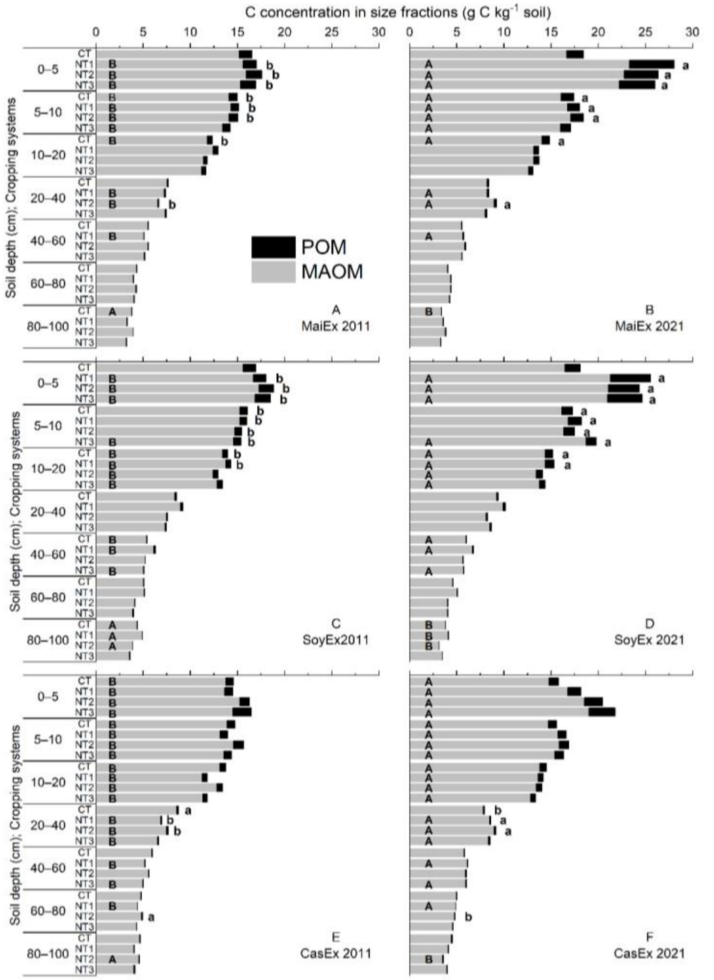

Figure 4. ~~Amount of~~ Carbon stock in mineral-associated and particulate organic matter (MAOM and POM) ~~and particulate organic matter (POM)~~ fractions across the whole profile (01–100 cm) in 2011 and 2021 under different treatments and experiments~~cropping systems~~. CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no--till mulch-based cropping systems

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associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems under NT systems with no-till mulch-based cropping systems associated with cropping systems~~CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till mulch-based cropping systems associated with different cropping systems~~ as described in Table 1. The u~~U~~ppercase letters on the bars and lowercase letters in front of the bars indicate a significant difference (Tukey’s test; *p*~~P~~ < 0.05) in C ~~c~~sto~~n~~ck~~entration~~ in MAOM and POM, respectively, between 2011 and 2021 for the same treatment and soil depth.

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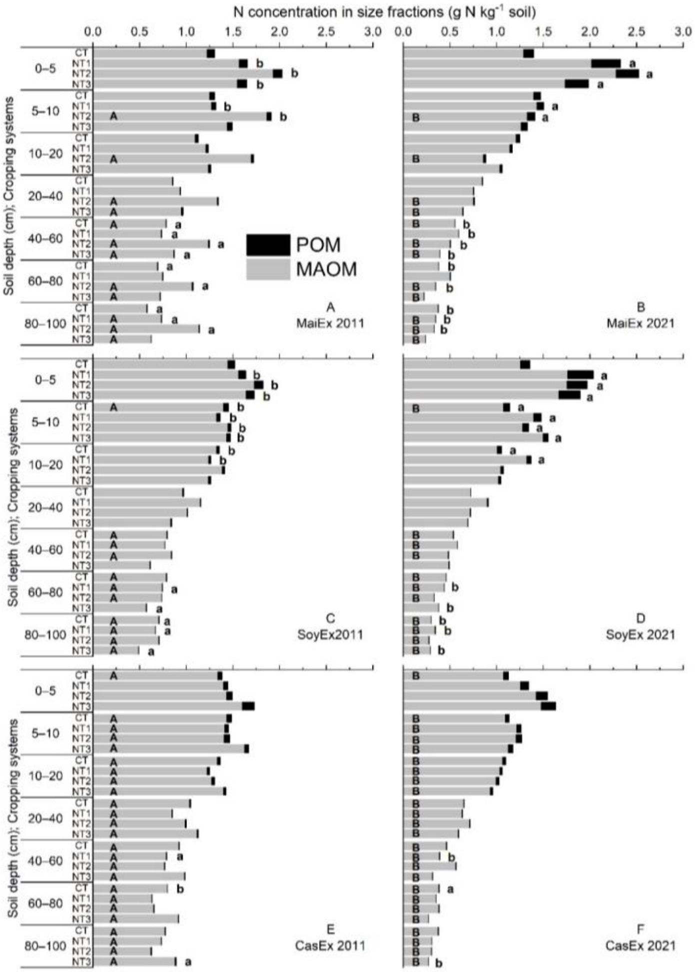

3.3.2 N stock in size fractions

Over the past decade (2011–2021), ~~tillage and~~ cropping systems had varying effects on the stocks of N-

POM and N-MAOM across soil depths and the experiments (Fig. 5, ~~with~~ Tables S8 and S9 ~~in the supplementary as duplications~~). In 2021, N-POM stock increased significantly ($p < 0.05$) in the topsoil (0–10 cm) under all the NT systems in MaiEx and SoyEx, with similar amounts of 0.10 and 0.01 Mg N ha^{-1} in the 0–5 and 5–10 cm, respectively (Figs. 5B and 5D). Below 10 cm, ~~overall,~~ N-POM stock remained constant under all the NT systems in both experiments, except for the depletion trend found under a NTR system, in particular under NTR2-Mz below 40 cm and NTR2-Sb below 60 cm (Figs. 5B and 5D). In contrast to MaiEx and SoyEx, in CasEx, none of NT systems increased N-POM stock in the top soils, but NTM-Cs and NTR-Cs systems significantly ($p < 0.05$) depleted it below 20 cm (Fig 5F).

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In 2021, monocropping of soybean under conventional tillage (CTM-Sb) significantly accumulated N-POM stock in the tilled layers (5–10 and 10–20 cm) with an amount of 0.01 Mg N ha^{-1} across the two layers, but the significant depletion ($p < 0.05$) at a similar amount was observed below 40 cm (Fig. 5D). Monocropping of upland rice over a decade and recent shift~~ed~~ to maize under conventional tillage (CTM-Mz) did not change the N-POM stock across the soil profile (Fig. 5B), whereas the N-POM stock under CTM-Cs soil remained stable in the top 20 cm, but significantly declined by -0.01 Mg N ha^{-1} from 20 to 60 cm (Fig. 5E and 5F).

Surprisingly, from 2011 to 2021, none of the tillage or cropping systems increased N-MAOM stock, but decreased it with varying soil depths and experiments (Fig. 5). In MaiEx and SoyEx, N-MAOM stock remained unchanging under NTM system (i.e., NTM-Mz and NTM-Sb) from 0 to 40 cm but declined significantly ($p < 0.05$) below 40 cm with the rate ranging from -0.036 to -0.063 Mg N ha^{-1} yr^{-1} (Figs. 5A and 5C). Under NTR-Mz and NTR-Sb, the significant decrease of N-MAOM stock was detected below 5 cm to subsoil layers, but this was inconsistent between the two NTR systems (NTR1 and NTR2) and soil depths, with depletion rates ranging from -0.023 Mg N ha^{-1} yr^{-1} in the near soil surface to -0.140 Mg N ha^{-1} yr^{-1} in the bottom of the soil profile (Figs. 5A and 5C). In CasEx, the N-MAOM stock in the surface layer (0–5 cm) did not change under all the NT systems (NTM-Cs, NTR1-Cs, and NTR2-Cs), but decreased significantly ($p < 0.05$) below 5 cm with the annual depletion rates ranging from -0.009 to Mg N ha^{-1} yr^{-1} in the 5 cm to -0.111 Mg N ha^{-1} yr^{-1} in the subsoil profile (Fig. 5E and 5F).

In 2021, the N-MAOM stock of the CTM-Mz soil remained steady at the 0–40 cm, whereas depletion was detected from 40–100 cm at rates ranging from -0.032 to -0.058 Mg N ha-1 yr-1 (Figs. 5A and 5B). CTM-Sb did not preserve N-MAOM stock even in tilled layers over the past ten years, but depleted it significantly below 5 cm to subsoil depths at rates of -0.016 to -0.073 Mg N ha^{-1} yr^{-1} (Figs. 5C and 5D), while a significant decrease in N-MAOM stock was observed throughout the soil profile (0–100 cm) with a depletion of -0.013 to -0.081 Mg N ha^{-1} yr^{-1} (Figs. 5E and 5F).

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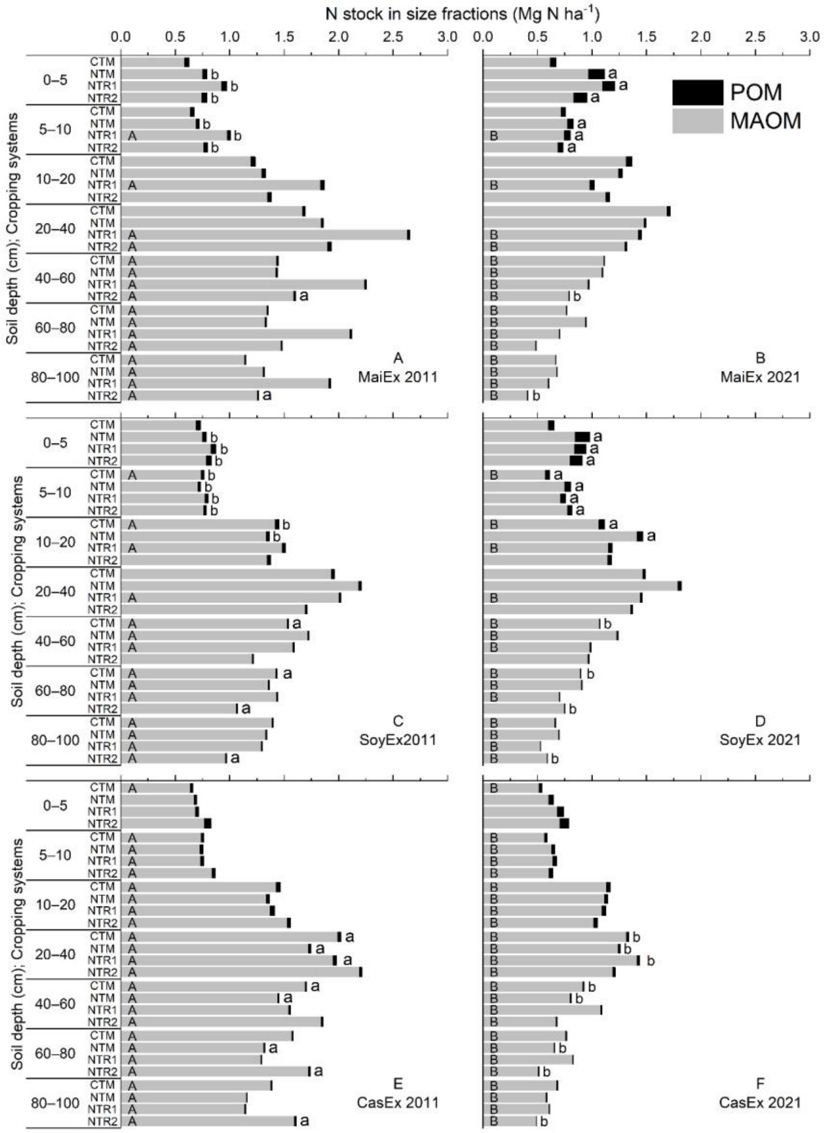

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Figure 5. ~~Amount of~~ TN stock in mineral-associated ~~organic matter (MAOM)~~ and particulate organic matter (MAOM and POM) fractions across the whole profile (01–100 cm) in 2011 and 2021 under different treatments and experiments ~~cropping systems~~. CTM: monocropping under conventional tillage; NTM: monocropping under NT systems with no- till mulch-based cropping systems associated with different crop sequences, and NTR1 and NTR2 refer to bi-annual crop rotational systems under NT systems with no-till mulch-based cropping systems associated with cropping systems as ~~CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till mulch-based cropping systems associated with different cropping systems~~ described in Table 1. The u~~U~~ppercase letters on the bars and lowercase letters in front of the bars indicate a significant difference (Tukey's test; *p*~~P~~ < 0.05) in TN st~~e~~o~~n~~ck~~entration~~ in MAOM and POM, respectively, between 2011 and 2021 for the same treatment and soil depth.

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4 Discussion

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4.1 Change in SOC stock

Despite the ~~varied~~contrasted effects among the NT systems and the experiments, our~~This~~ study showed that ~~quantified the impacts~~ adopting NT systems with the use of cover crops ~~and high biomass C inputs~~ in the long-term significantly ~~of cropping systems on changes~~ increased SOC ~~and N~~ stock~~s and their fractions down to 100 cm depth in three long-term annual crop production experiments. Over 10 years, NT systems modified the SOC stock~~ ~~and its vertical distribution~~ (Table 3).

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Several studies reported that long-term NT adoption accumulated SOC stock only on the surface soils, but the stock did not differ from CT when considering the whole soil profile (Blanco-Canqui and Lal, 2008; Luo et al., 2010; Blanco-Canqui et al., 2011; Du et al., 2017; Xiao et al., 2020). For example, a recent meta-analysis from 86 studies covering a range of crop productions across the world, ~~(~~Xiao et al., (2020) found that NT systems significantly accumulated the SOC stock only in the top 0–5 cm, and no significant change was found below 5 cm. Across climatic conditions, soil types, and various cropping systems in China, based on 95 comparisons between NT and CT, adopting NT led to increase in SOC stock by 3.8% in the upper 20 cm layer but to a decrease in SOC in the 30–40 cm layer (Du et al., 2017).

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Similarly, from a systematic review of global data of 69 paired-experiments, ~~(~~Luo et al., (2010) reported that long-term NT adoption only significantly affected SOC stock in the top 0–10 cm but not down to 40 cm depth. The authors also reported that increasing crop species diversity resulted in a lower SOC accumulation in the surface and a greater SOC loss in deeper layers.

SOC stock changes reported under NT systems may differ according to climate, soil type and cropping systems (Paustian et al., 1997; Six et al., 2002; Bayer et al., 2006; Ogle et al., 2012; Virto et al., 2012). Soils in the tropical climate require diversified and large amounts of C inputs for NT viability due to fast residue decomposition and difficulty in maintaining soil cover (Séguy et al., 2006; Castro et al., 2015). In the same experiments as in our study, Hok et al. (2015) reported that NT systems with diverse crop species significantly accumulated SOC at the surface 0–5 cm after 4 years of NT adoption. Our study ~~Although there is variability in SOC stock accumulation and its vertical distribution among the three NT systems, our results~~ revealed that NT systems significantly increased SOC stock, although there wa~~i~~s variability among the NT systems~~,~~ and across the three experiments in the accumulation rates in the subsoil layers (Table 2) ~~with accumulation rate ranging from 0.38 to 0.66 Mg C ha^{-1} yr^{-1} in 0–10 cm under SoyEx, from 0.85 to 0.96 Mg C ha^{-1} yr^{-1} in 0–20 cm under MaiEx, and from 0.69 to 0.86 Mg C ha^{-1} yr^{-1} in 0–40 cm under CasEx~~. Considering the cumulative SOC stock, ~~our results revealed that~~ all the NT systems significantly (*p*~~P~~ < ~~>~~ 0.05) increased cumulative SOC stock across the whole soil profile in MaiEx and CasEx. In SoySx, significant increase in cumulative SOC stock was limited to the top 0–20 cm under NTM-Sb ~~monocropping~~, whereas NTR-Sb ~~crop rotation systems~~ had significantly accumulating SOC stock from 0 to 80 cm depths (~~Table 5) (the cumulative SOC stock in 2011 is presented in~~ Table S10~~9~~ ~~in the supplementary materials~~).

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~~When considering the whole profile (0–100 cm), the annual SOC accumulation rate under NTs ranged from 0.65 to 1.00, 0.86 to 1.47, and 0.70 to 1.07 Mg C ha^{-1} yr^{-1} in SoyEx, MaiEx and CasEx, respectively.~~ Consistent with our findings, with the intensive NT systems and high C inputs retained to the soils, other studies reported that long-term NT with the use of cover crops increased SOC stock beyond the surface and the whole soil profile (Diekow et al., 2005; Boddey et al., 2010; Olson et al., 2014). From three long-term experiments (15–26 years) on Ferralsols in South Brazil, no-tillage with intensive cropping systems of maize and soybean production increased SOC with annual accumulation rates between 0.04 and 0.88 Mg ha^{-1} in 0–30 cm, and from 0.48 to 1.53 Mg ha^{-1} yr^{-1} 0–100 cm (Boddey et al., 2010). After 12 years of NT adoption with the use of cover crops for soybean and maize rotation in a humid continental sloping land in Illinois, USA, SOC stock recovered from its initial SOC loss under CT before the experiment implementation, with accumulation rates of 0.42, 0.78, and 1.21 Mg C ha^{-1} yr^{-1} at 0–15, 15–75, and 0–75 cm, respectively (Olson et al., 2014).

SOC storage and stabilization could be explained by several processes: (i) continuous supplies of large quantities and diverse qualities of plant biomass-C inputs to the soil (Sá et al., 2014); (ii) the transformation of this biomass-C by microbial communities into various organic C forms (Frasier et al., 2016; Schmidt et al., 2019); (iii) the stabilization of newly derived C by physical protection, binding with organo-mineral particles, and biochemically stabilization through the formation of recalcitrant soil organic matter (Six et al., 2002); and (iv) distribution of SOC over the soil profile through biological processes, from root systems (Lorenz and Lal, 2005) and soil fauna (Lavelle et al., 2016).

In NT systems, multiple crop species were sown in the same unit area of land through the rotation of cash crops and the use of cover crops by intercropping or during the fallow period, producing a large quantity

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and diverse quality of C inputs above- but also below-ground that were retained to the soils. In our experiments, the annual biomass C inputs retained in the NT soils ranged from 3.61 to 6.07 Mg ha^{-1} yr^{-1}, versus 1.36 to 2.20 Mg ha^{-1} yr^{-1} under CTM (Table 1). In a ~~clayed~~ clayey Oxisol of Brazil, a 16-year-old experiment revealed that NT was more effective than CT at converting biomass-C inputs into SOC, with a C conversion ratio in 0–40 cm depth of 0.35 compared to 0.07 under NT and CT, respectively (Sá et al., 2014). In addition, integration of cover crops into the crop production system led to a significant increase in SOC. From the observation of 139 plots at 37 sites from the tropics and temperate zone and diverse soil types, Poeplau and Don (2015) reported that the use of cover crops led to an average SOC accumulation rate of 0.32 Mg C ha^{-1} yr^{-1} at 22 cm depth. Association of tropical legume cover crops in maize production led to increased SOC stock in the surface as well as the whole soil profile. Diekow et al. (2005) found that the SOC accumulation rate in the legume-based cropping systems was 0.83 and 1.42 Mg C ha^{-1} yr^{-1} in the 0–17.5 cm and 0–107.5 cm layer, respectively after 17 years of NT adoption in a Brazilian Acrisol. From a 30-year-old experiment in a Brazilian Acrisol, legume cover crops were twice as effective in storing C as mineral N fertilization, with 1 kg of residue C input being transformed to 0.15 kg of SOC (Veloso et al., 2018).

Considering the challenges faced by smallholder farmers in Cambodia with low financial resources and/or high level of indebtedness, the main strategy should focus on enhancing nutrients cycling through continuous biomass-C inputs under no-till cropping systems plus a combination of actions to reduce nutrient removal from cassava fields through the non-removal of leaves and of a proportion of stalks, that may also help to reduce the impact of nutrients deficiency. In addition, the tolerance of cassava to acidic soil, its ability to grow on depleted and degraded soils related to the occurrence and synergistic effects of

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arbuscular mycorrhizal fungi (Howeler et al., 1982; Howeler and Sieverding, 1983), and plant growth-promoting rhizobacteria ~~(PGPR)~~ (Balota et al., 1999), its nutrient recycling ability through leaf litter and when the stalks are not used as planting materials and kept into the field, could be used to ~~advance in~~improve soil and cropping system sustainability (Fermont et al., 2008). This possible use by farmers of cassava cropping systems as a strategy for regenerating soil fertility was also emphasized by Saïdou et al., (2004) and Adjei-Nsiah et al., (2007) in Benin and Ghana, respectively.~~During the decomposition process, microbial communities use the rapidly decomposable materials as energy sources, while the recalcitrance and other labile compounds materials act as the glue to bind soil mineral particles together (Witzgall et al., 2021). This process is a pathway for the formation of soil micro-aggregates (Bot and Benites, 2005). The continuous supply of biomass C inputs to the soil associated with microbial decomposition without soil mechanical disturbance creates a favourable environment for the emergence of soil macroaggregates (Crews and Rumsey, 2017). Organic carbon inside soil aggregates is physically protected from microbial oxidation as well as strongly associated with the organo minerals, leading to SOC stabilization over time (Powlson et al., 1987; Lützow et al., 2006). In the same experiments as in our study but after 3 years of NT adoption, Hok et al. (2021) reported that soil aggregation was one of the main stabilization mechanisms, providing physical protection to the newly derived C into the soil microaggregates protected by macroaggregates. From our knowledge of the literature, the high SOC accumulation rate recorded under cassava-based NT cropping systems is relatively unique and, in addition to the residues of cover crops and maize under the biannual cropping system, the nature of the cassava residues that was retained into the field with high cellulose and lignin contents (Veiga et al., 2016) may explain this result. Considering the challenges faced by smallholder farmers in Cambodia with low~~

~~financial resources and/or high level of indebtedness, the main strategy should focus on enhancing nutrients cycling through continuous biomass-C inputs under no-till cropping systems plus a combination of actions to reduce nutrient removal from cassava fields through the non removal of leaves and of a proportion of stalks, that may also help to reduce the impact of nutrients deficiency. In addition, the tolerance of cassava to acidic soil, its ability to grow on depleted and degraded soils related to the occurrence and synergistic effects of arbuscular mycorrhizal fungi (Howeler et al., 1982; Howeler and Sieverding, 1983), and plant growth-promoting rhizobacteria (PGPR) (Balota et al., 1999), its nutrient recycling ability through leaf litter and when the stalks are not used as planting materials and kept into the field, could be used to advance in soil and cropping system sustainability (Fermont et al., 2008). This possible use by farmers of cassava cropping systems as a strategy for regenerating soil fertility was also emphasized by Saïdou et al., (2004) and Adjei-Nsiah et al., (2007) in Benin and Ghana, respectively.~~

Long-term NT adoption has been shown to significantly improve soil structure, soil porosity and pore connectivity (Cooper et al., 2021) contributing to the improvement of water infiltration, gas exchanges and microbial activities, and roots development to deeper soil profile (Rosolem et al., 2016). In addition, aerobic condition of soil aggregates would enhance SOC stability in unsaturated soils (Zhang et al., 2021). Sisti et al. (2004) showed that increased C accumulation in NT soil below 30 cm depth could be explained by greater root density when compared with CT. Another possibility is that organic residues from upper layers were transported downward by soil meso- and macro-fauna organisms, which could have been favoured by better environmental conditions provided by the continuous C flow and soil structure enhancement under NT systems (Lavelle et al., 2016).

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In our study, the SOC stock in the whole soil profile (0–100 cm) under CTM and for the three experiments remained ~~constant~~stable, which could be attributed to the fully retained crop residues (i.e., mungbean, rice, and maize) in MaiEx and (i.e., sesame and soybean) in SoyEx and partially retained cassava's fallen leaves and stalks in CasEx (Table 1), indicating that it reached a new SOC equilibrium~~ stage~~. The high clay content ~~has ~~also contributed to the stabilisation of the MAOC that accounted, in 2021, for 97.2% of the carbon ~~concentrations~~stock along the soil profile.

Under a synchronic approach, considering CTM as the reference, the SOC stock change rates in 2021 under NT systems ranged from 0.13 to 0.60, -0.50 to 0.43, and 0.10 to 0.46 Mg C ha^{-1} yr^{-1} in MaiEx, SoyEx, and CasEx, respectively (Fig. 6). When compared with the diachronic approach, this corresponds to an underestimation of 146 to 536%, 51 to 347%, and 51 to 997% in MaiEx, SoyEx, and CasEx, respectively (Table 3). In Brazil, from on-farm assessments of the SOC dynamics under long-term NT systems in tropical heavy claye~~d~~y soils Neto et (al., 2010) and Junior et al., (2013) reported that synchronic approach led to ~~the ~~biased ~~in the ~~annual SOC accumulation rates under NT systems when compared with diachronic approach. The main factors associated with the errors could be the underlying heterogeneities of the soil conditions prior to the conversion to NT systems that are hard to capture despite all the steps of the methodologically precautious measurements being implemented properly (Neto et al., 2010; Junior et al., 2013). Our findings clearly emphasize the importance of the diachronic approach in accurately estimating the effects of long-term ~~CA and ~~NT systems on SOC storage~~, as well as providing a proper interpretation of their roles in climate change mitigation through SOC sequestration~~.

~~**Table 5**. Cumulative SOC stock in 2021 and cumulative SOC stock change 2021-2011.~~

~~**Experiments**~~[a]	~~**Approximate soil depth (cm)**~~	~~**Cropping systems**~~[b]							
		~~**CT**~~	~~**NT1**~~	~~**NT2**~~	~~**NT3**~~	~~**CT**~~	~~**NT1**~~	~~**NT2**~~	~~**NT3**~~
		~~**Cumulative SOC stock 2021 (Mg C ha^{-1})**~~				~~**Cumulative SOC stock change 2021-11 (Mg C ha^{-1})**~~			
~~MaiEx~~	~~0-10~~	~~19.98 Ab~~	~~25.93 Aa~~	~~25.18 Aa~~	~~24.40 Aa~~	**~~1.24~~**	**~~8.30~~**	**~~7.06~~**	**~~6.64~~**
	~~0-20~~	~~38.26 A~~	~~42.24 A~~	~~42.26 A~~	~~40.72 A~~	**~~3.53~~**	**~~9.37~~**	**~~9.56~~**	**~~8.49~~**
	~~0-40~~	~~58.16 A~~	~~60.85 A~~	~~62.55 A~~	~~59.37 A~~	**~~4.61~~**	**~~10.94~~**	**~~14.03~~**	**~~9.22~~**
	~~0-60~~	~~70.74~~	~~73.03 A~~	~~75.29 A~~	~~71.68 A~~	~~4.19~~	**~~11.76~~**	**~~15.07~~**	**~~9.40~~**
	~~0-80~~	~~79.75~~	~~82.61 A~~	~~84.93 A~~	~~81.01 A~~	~~3.01~~	**~~12.45~~**	**~~14.89~~**	**~~9.21~~**
	~~0-100~~	~~86.92~~	~~90.13 A~~	~~92.90 A~~	~~88.27 A~~	~~1.75~~	**~~12.97~~**	**~~14.71~~**	**~~8.59~~**
~~SoyEx~~	~~0-10~~	~~19.41b~~	~~22.91 Aab~~	~~24.19 Aa~~	~~24.38 Aa~~	~~0.46~~	**~~4.00~~**	**~~4.96~~**	**~~5.61~~**
	~~0-20~~	~~37.76~~	~~39.70 A~~	~~41.46 A~~	~~41.81 A~~	~~1.52~~	**~~3.76~~**	**~~6.61~~**	**~~6.37~~**
	~~0-40~~	~~60.10~~	~~62.35~~	~~60.72 A~~	~~61.50 A~~	~~3.45~~	~~5.43~~	**~~8.55~~**	**~~8.19~~**
	~~0-60~~	~~75.30~~	~~78.21~~	~~73.72 A~~	~~74.59 A~~	~~4.82~~	~~6.46~~	**~~9.81~~**	**~~9.88~~**
	~~0-80~~	~~86.45~~	~~90.16~~	~~83.20 A~~	~~83.90 A~~	~~5.22~~	~~7.03~~	**~~9.96~~**	**~~10.24~~**
	~~0-100~~	~~95.22~~	~~99.53~~	~~90.23~~	~~91.15~~	~~4.78~~	~~6.53~~	~~9.18~~	~~10.03~~
~~CasEx~~	~~0-10~~	~~17.41 Ac~~	~~19.00 Abc~~	~~20.50 Aab~~	~~21.43 Aab~~	**~~1.46~~**	**~~3.57~~**	**~~3.09~~**	**~~3.86~~**
	~~0-20~~	~~34.56 Ab~~	~~35.66 Aab~~	~~37.13 Aab~~	~~37.66 Aa~~	**~~2.39~~**	**~~6.04~~**	**~~3.98~~**	**~~5.69~~**
	~~0-40~~	~~52.74~~	~~54.50 A~~	~~57.90 A~~	~~56.93 A~~	~~1.45~~	**~~8.28~~**	**~~6.88~~**	**~~8.57~~**
	~~0-60~~	~~65.86~~	~~67.93 A~~	~~71.84 A~~	~~69.92 A~~	~~1.00~~	**~~9.72~~**	**~~8.05~~**	**~~9.82~~**
	~~0-80~~	~~76.97~~	~~78.71 A~~	~~82.46 A~~	~~80.10 A~~	~~1.20~~	**~~10.58~~**	**~~7.93~~**	**~~10.25~~**
	~~0-100~~	~~86.44~~	~~87.42 A~~	~~91.07 A~~	~~88.01 A~~	~~1.35~~	**~~10.68~~**	**~~6.97~~**	**~~9.46~~**

[a] ~~MaiEx: Maize-based experiment; SoyEx: Soybean-based experiment; and CasEx: Cassava-based experiment.~~

[b] ~~CT: conventional tillage; NT: no-till, NT1, NT2, and NT3 refer to no-till associated with cropping systems as described in Table 1. Uppercase letters accompanying the values indicate significant difference within the same treatment between 2011 and 2021 (diachronic) at the same soil depth at P ≤ 0.05 (Tukey's test). Values of cumulative SOC stock change in bold indicate changes for a given treatment and depth between 2021 and 2011 are significantly different from 0 at P ≤ 0.05 (Tukey's test).~~

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~~In our study, the SOC stock in the whole soil profile (0–100 cm) under CT and for the three experiments remained constant, which could be attributed to the fully retained crop residues (i.e., mungbean, rice, and maize) in MaiEx and (i.e., sesame and soybean) in SoyEx and partially retained cassava's fallen leaves and stalks in CasEx (Table 1), indicating that it reached a new SOC equilibrium stage. The high clay content has also contributed to the stabilisation of the MAOC that accounted, in 2021, for 97.2% of the carbon concentrations along the soil profile.~~

~~Under a synchronic approach, considering CT as the reference, the SOC stock change rates in 2021 under NT systems ranged from 0.13 to 0.60, -0.50 to 0.43, and 0.10 to 0.46 Mg C ha^{-1} yr^{-1} in MaiEx, SoyEx, and CasEx, respectively (Fig. 6). When compared with the diachronic approach, this corresponds to an underestimation of 146 to 536%, 51 to 347%, and 51 to 997% in MaiEx, SoyEx, and CasEx, respectively (Table 3). In Brazil, from on-farm assessments of the SOC dynamics under long-term NT systems in tropical heavy clayed soils Neto et (al., 2010) and Junior et al., (2013) reported that synchronic approach led to the bias in the annual SOC accumulation rates under NT systems when compared with diachronic approach. The main factors associated with the errors could be the underlying heterogeneities of the soil conditions prior to the conversion to NT systems that are hard to capture despite all the steps of the methodologically precautious measurements being implemented properly (Neto et al., 2010; Junior et al., 2013). Our findings clearly emphasize the importance of the diachronic approach in accurately estimating~~

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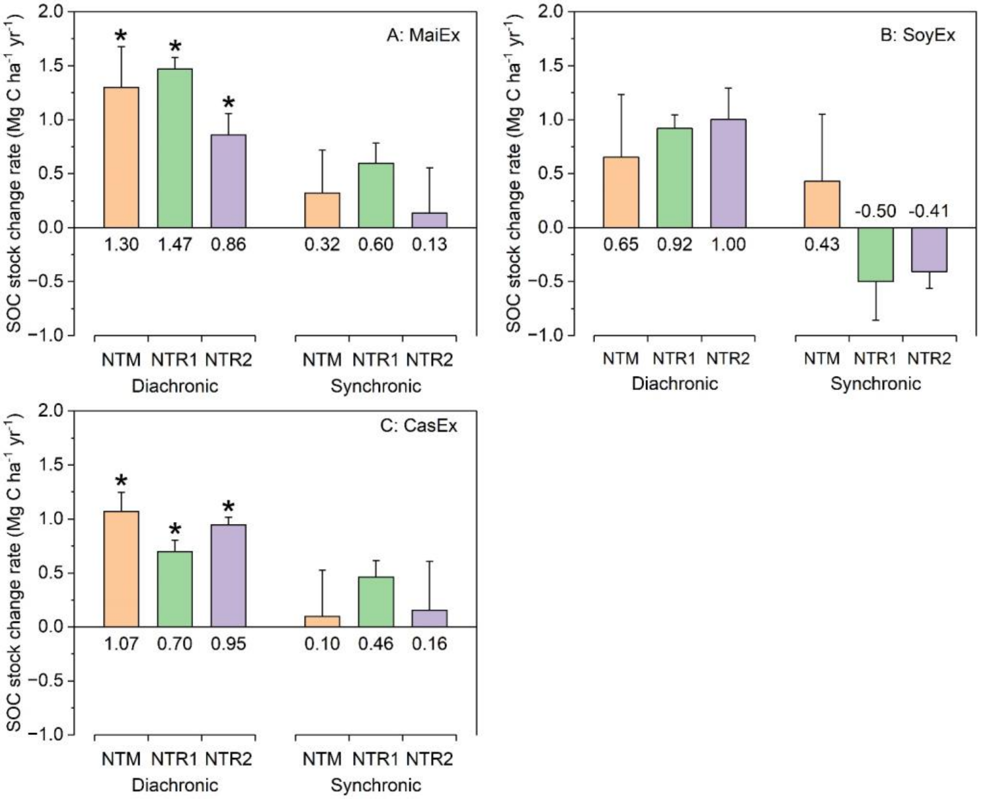

~~the effects of long-term CA and NT systems on SOC storage, as well as providing a proper interpretation of their roles in climate change mitigation through SOC sequestration.~~

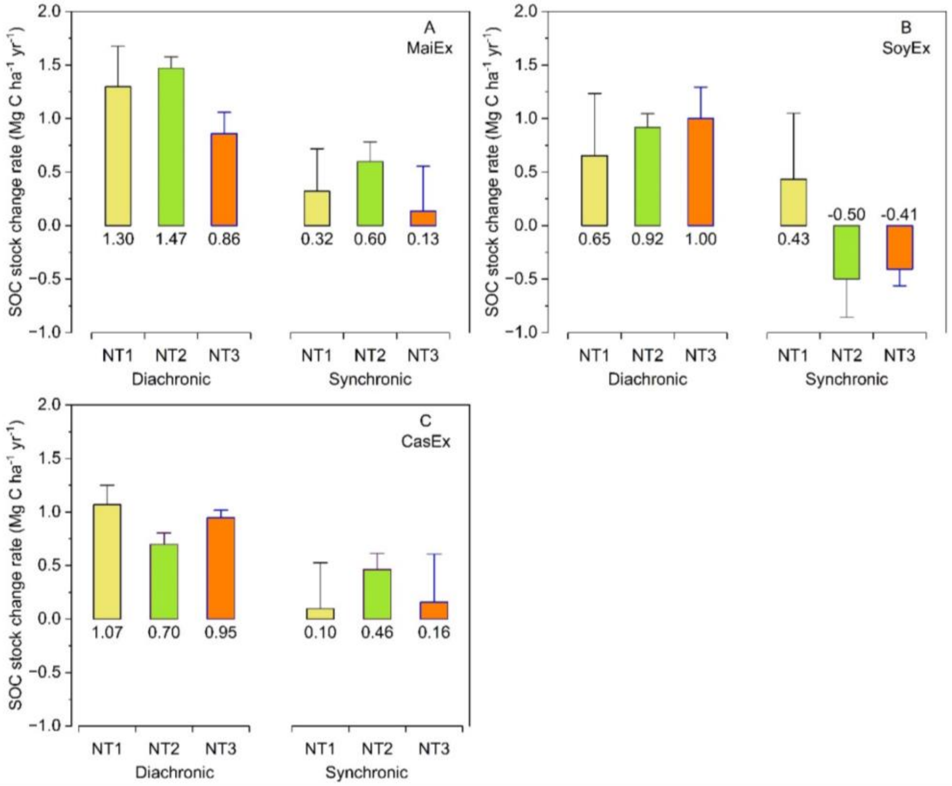

Figure 6. Comparison between the diachronic and synchronic approaches to estimate SOC stock change rate (0–100 cm) from 2011 to 2021 under NT systems in the tropical red Oxisol of Cambodia (n = 3; error bars = SE). A: MaiEx (maize-based trial); B: SoyEx (soybean-based trial); and C: CasEx (cassava-based experiments). CAM: monocropping under conservation agriculture with no-till mulch-based cropping systems associated with different crop sequences, and CAR1 and CAR2 refer to bi-annual crop rotational systems under conservation agriculture with no-till mulch-based cropping systems associated with different crop sequences described in Table 1. The stock change rates under diachronic were calculated by subtracting the stock of the same treatment in 2021 from the stock in 2011 and dividing by the number of years between the 1st and 2nd samplings (10 years), while the stock change rates of CA systems in 2021 under synchronic were calculated by subtracting the stock of each CA treatment from the stock of CTM in 2021, considered the control, and dividing by the number of years between the 1st and 2nd

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samplings (10 years). (*) indicates a significant difference (Tukey's test; $p < 0.05$) in SOC stock between 2011 and 2021. Positive values indicate SOC stock accumulation; negative values indicate SOC loss.~~by considering SOC stock under CT as the control for the stock change rates of NT systems in 2021 for the calculation in the synchronic approach (n = 3; error bars = SE).~~

4.2 Change in N stock

In addition to increasing SOC stock in the surface and the whole soil profile, Diekow et al. (2005) found that soil~~ total~~ TN stock was significantly increased by an average of 27% in~~at~~ the surface (0–17.5 cm) and by 6% in the whole profile (0–107.5 cm) after 17 years of NT maize and ~~with the use of~~ tropical legume intercropping~~cover crops~~ and N fertilization compared ~~in comparison to~~ with its original state under native grassland ~~as a reference~~ of~~in a~~ Brazilian Acrisol. Sá et al., (2014) reported a s~~trong positive~~ignificant ~~relationship~~ correlation ($R^2 = 0.89$, $P < 0.0002$) between ~~the~~ soil N and SOC stock accumulation. E~~; e~~ach unit of N stock accumulation contributed to the sequestration of 10.2 Mg C ha^{-1} at the top 0–10 cm under long-term (16-year) continuous NT maize-based production of Brazilian's Oxisol. However, the diachronic assessment in our study showed that ~~soil~~T~~–~~N stock under NT systems significantly increased only in the topsoil (0−5 cm) in MaiEx and SoyEx, while the stock remained stable in CasEx (Table 3). The significant decline of TN stock under NT systems, although with variability across the NT systems and the experiments, was detected below 20 cm. When considering the whole profile (0–100 cm), significant depletion of N stock was observed under the NT monocropping systems, with a loss rate at -0.10 and -0.17 Mg N ha^{-1} yr^{-1} in SoyEx (NTM~~1~~-Sb) and CasEx (NTM~~1~~-Cs), respectively. Under NT crop rotation systems, despite non-significant, TN stock tended to decrease across the three experiments, with a depletion rate ranging from -0.03 to -0.09 Mg N ha^{-1} yr^{-1} (Table 4).

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The depletion of TN stock under NT was reported from short- (Wuaden et al., 2020) to longer-term NT adoption (Delgado, 2023). From a short-term (5-year) conversion of native grassland to cropland under NT adoption with a double cropping with maize as a cash crop followed by black oat as a cover crop in Brazil's Rhodic Nitosol, NT soils had significant losses of soil total N in comparison with the original stocks under grassland throughout the soil profile, with the exception of the 0−5 and 10−20 cm soil layers. Considering the whole profile (0–60 cm), soil total N was depleted by -1.7 Mg N ha^{-1}, equivalent to an annual loss rate of -0.34 Mg N ha^{-1} yr^{-1} after 5 years of grassland conversion to NT (Wuaden et al., 2020). Results from a 12-year experiment in the US (0–~~-~~120 cm depth) in an irrigated NT continuous maize rotation where mineral N were applied at different rates indicated that even NT could potentially have significant net N loss with an average loss of -~~–~~15 kg N ha^{-1} yr^{-1} at the top 30 cm of soil regardless of N application rate (Delgado, 2023).

In our study, it is a rather surprising finding to observe an increase in SOC and a simultaneous soil TN depletion. Associating legume cover crops in the cropping system did not enhance soil N through biological N fixation (Rosolem et al., 2016). In general, N is an important factor contributing to SOC storage (De Vries, 2014; Kirkby et al., 2014). Nutrient reserves are among other factors that determine soil C storage capacity (Lal, 2018). Therefore, more studies on nutrient availability and their stoichiometry relationship including in deeper layers (>100 cm), on the N use efficiency and N cycling are needed to understand the driving mechanisms of the N dynamics under these NT systems.

Nitrogen uptake and/or N priming effects from the cover crops, among other factors, could possibly have resulted in N loss~~ in our study~~. Priming effects are short-term changes in the turnover of soil N caused by the addition of organic or mineral fertilizer, the mechanical treatment of soil, its drying and rewetting

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(Kuzyakov et al., 2000), and the exudation of organic substances in the rhizosphere by living plants (Kuzyakov, 2002). These effects can occur immediately or very shortly after the addition of a specific substance to the soil and are larger in soils rich in C and N than those in poor soils (Kuzyakov et al., 2000). In our experiments, under CA systems, the soils are year-round protected by the cover crops established through association or succession with the main crops (maize, soybean, and cassava) and continue to grow after the main crop harvest. Several species of drought-tolerant and fast-growing cover crops (stylo, brachiaria, cowpea, sorghum, pearl millet, and su~~n~~nhemp), which are commonly used in our experiments as a single or mixture (Table 1), are good examples of remaining green throughout the dry season with root exudates that may have enhanced the priming effect. In addition, the symbiosis relationship between the cover crops and rhizobia during the dry season could also be low due to low soil moisture content, therefore resulting in high N uptake from the soil by those cover crops. Their drought-tolerant characteristics allow these species to cross the dry season, even with little or no rain for more than 4 months in the dry season. Their fast-growing characteristics, along with the species diversity, produced a large amount of biomass annually and were retained in the soil at the termination of the cultivation of the main crops (Table 1), which may create conditions for the N uptake or N priming effects to happen. ~~Therefore, the m~~Measurement of N content and the estimation of biological nitrogen fixation by the legume cover crops using the ^{15}N~~15~~ isotopic technique should be conducted to better understand N dynamics in the different systems.~~explain the N uptake or N priming effects.~~

To date, few studies on the impact of no-till systems on N gains or N losses, N use efficiency and changes in soil N have been conducted, and the results vary depending on the period of NT adoption and sampling depths (Congreves et al., 2017; Delgado, 2023). Further research is needed to understand the driving

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mechanism of the N dynamics under NT systems by considering deeper layers (>100 cm) for making informed decisions regarding sustainable soil fertility management and crop production systems. Positive accumulation rates of SOC stock, recorded under NT systems, could not be sustained on the long-term as the depletion of the TN stock may lead to nutrient scarcity of other nutrients (P, S, Ca^{2+} and Mg^{2+}) that is the driving force limiting SOC accumulation. Further analysis is needed to assess the coming changes in SOC and N stocks along with the content of nutrients and its potential impact on the rate of SOC accumulation or depletion (Kirkby et al., 2013).

~~4.3 SOC and N stocks recovery after land use change~~

~~Conversion of native vegetation to cropland under conventional plough-based tillage depletes SOC (Sisti et al., 2004; Sá et al., 2015; Wuaden et al., 2020) due to soil structure disruption by the mechanical disturbance, low C inputs, and accelerates the SOC mineralisation rate by exposing SOC that was encapsulated inside soil aggregates to microbial oxidation (Balesdent et al., 2000). Even if this comparison with RV was restricted to 0-20 cm depth, the present study showed that NT systems can restore SOC stock that was lost during crop production under conventional tillage after the conversion of native vegetation to cropland and before the experiments' establishment. At 0–20 cm depth, the annual SOC accumulation rates of NT systems ranged from 0.85 to 0.96, 0.38 to 0.67, and 0.40 to 0.61 Mg C ha^{-1} yr^{-1} under MaiEx, SoyEx and CasEx, respectively. This could be attributed to the long-term NT systems adoption with multiple crop species through cash crop rotation and cover crop association producing high and diverse biomass-C inputs retained in the soil, leading to an increase in SOC stock across the whole profile. After 12 years of experimentation, Neto et al., (2010) found that SOC stocks under NT mulch-~~

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~~based management systems were no longer significantly different from the stocks of natural Cerrado vegetation in Brazil. Sá et al., (2014) reported the recovery of SOC stock under NT to the reference vegetation an accumulation rate of 0.84 Mg C ha^{-1} yr^{-1} at 0–20 cm after 16 years of continuous NT with an average annual biomass C input of 4.40 Mg ha^{-1} yr^{-1}.~~

~~Noticeably, SOC stock under CT was significantly lower than RV in 2011 in all the three experiments, but SOC stock did not differ from RV in SoyEx and MaiEx, while the stock remained stable in CasEx in 2021 (Fig. 3). Because the SOC stock under CT soils have been depleted over the 70 years after natural forest conversion to cropland (see the history of land use change in Hok et al., 2015) they represent a potential C sink. Therefore, the gain of SOC stock under CT could be explained by the annual full retention of crop residues in MaiEx and SoyEx over the experiment period (Table 1) along with the high clay content of this oxisol.~~

~~The recovery on N stock to RV under the NT systems in MaiEx and as well as all the tillage systems (including CT-Sb) in SoyEx could be explained by the association of legume crops and the use of mineral fertilizer as described in Table 1 and 2.~~

~~4.7~~3.4 Carbon and N in size fractions and stabilization processes in NT systems

Particulate organic matter (POM) and mineral-associated organic matter (MAOM) are the two main fractions of the SOC pools. They differ in physical and chemical characteristics as well as their turnover rates. POM is more sensitive to soil tillage and land use than MAOM and total SOC (Blanco-Moure et al., 2013; Kan et al., 2021). In all the experiments, ~~At 0–10 cm,~~ NT systems significantly increased C in both ~~-~~POM and ~~by 115%, 118%, in MaiEx and SoyEx, respectively, and by 37% in CasEx although this was not significant. NT systems also significantly enhanced C~~ MAOM fractions ~~by 33%, 21%, at~~ in the

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topsoil ~~0–10 cm~~ layer (Fig. 4). ~~depth in MaiEx and SoyEx and even deeper to the soil profile > 20 cm in CasEx (Fig. 4).~~ These increases could be attributed to the continuous supply of large amounts and diverse biomass-C inputs to the soil surface, through the diversity of the root systems along with the low level of soil disturbance under NT systems (Sá et al., 2014; Briedis et al., 2018).

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During the decomposition process, microbial communities use the rapidly decomposable materials as energy sources, while the recalcitrant and other labile compounds materials act as the glue to bind soil mineral particles together (Witzgall et al., 2021). This process is a pathway for the formation of soil micro aggregates (Bot and Benites, 2005). The continuous supply of biomass C inputs to the soil associated with microbial decomposition without soil mechanical disturbance creates a favourable environment for the emergence of soil macroaggregates (Crews and Rumsey, 2017). Organic carbon inside soil aggregates is physically protected from microbial oxidation as well as strongly associated with the organo-minerals, leading to SOC stabilization over time (Powlson et al., 1987; Lützow et al., 2006). In the same experiments as in our study but after 3 years of CA adoption, Hok et al., (2021) reported that soil aggregation was one of the main stabilization mechanisms, providing physical protection to the newly derived C into the soil microaggregates protected by macroaggregates. From our knowledge of the literature, the high SOC accumulation rate recorded under cassava-based CA cropping systems is relatively unique and, in addition to the residues of cover crops and maize under the bi-annual crop rotation system, the nature of the cassava residues that was retained into the field with high cellulose and lignin contents may explain this result (Veiga et al., 2016).

From an incubation of labelled litter, Witzgall et al., (2021) found that the occlusion of organic matter into aggregates and the formation of organo-mineral associations occurs concurrently on fresh litter

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surfaces regardless of soil structure. In addition, the increase in C-MAOM is attributed to C transfer from POM and other labile C pools. Over time, these compounds are transferred to more stable pools, creating associations with mineral colloids, with MAOM being more stabilized (Briedis et al., 2018). Rosolem et al. (2016) conducted 3-year successive experiments to assess the above- and belowground effects of a wide range of tropical grasses and legume cover crops, which were the same species that were used under the NT systems in our experiments, in combination with no-till soybean-based cropping systems in Brazilian tropical ~~clayed~~ clayey Rhodic Ferralsol on total organic C and N stocks and in POM fraction. They reported that the presence of C4 deep-root grass cover crops during the fallow period significantly increased total organic C and POM. Furthermore, legume cover crops contributed to maintaining the C/N ratio in the topsoil layers, which could keep increasing C over time. Beside the aboveground biomass, root systems of cover crops are also an important C inputs for SOC accumulation due to their capacity to grow deeper in the soil profile, during the dry season for some, exploring large volume of soil (Rosolem et al., 2016; Sokol et al., 2019), releasing large quantities of roots exudates, and recycling nutrients (Rosolem et al., 2005). The increase of ~~in~~ C stock in ~~-~~POM and ~~C-~~MAOM shows that NT systems with the use of cover crops is a key strategy to promote both SOC storage and long-term SOC stabilization.

In contrast to C-POM and C-MAOM, although the significant increase~~our results showed~~ of N-POM stock in the top 0–10 cm was observed under all the~~ that~~ NT ~~cropping~~ systems ~~only increased the amount of N~~in MaiEx and SoyEx, the depletion of N-MAOM stock was observed below 5 cm in CasEx and below 40 cm in MaiEx and SoyEx~~ POM~~. This raises questions about the N dynamics and N supplies through the use of mineral fertilizers, as well as N fixation through the use of legume crops in the NT cropping systems. Therefore, there is a need to conduct further research on N use efficiency, N cycles, and nutrient

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availability and their stoichiometry relationship by considering deeper layers (> 100 cm) to understand the mechanism driving N loss under NT systems in these long-term experiments. ~~at the uppermost soil surface (0–10 cm) in MaiEx and SoyEx over the past 10 years. However, significant decreases in N-POM and N-MAOM were observed below 40 cm and 5 cm, respectively (Fig. 5).~~

5 Conclusion

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The present study showed that, over 10 years, ~~variable~~ effects of ~~were observed among the three~~ NT systems on SOC and TN stocks and ~~pools~~fractions varied across ~~and in~~ the three NT systems and the experiments. All the NT cropping systems significantly increased SOC stock in the surface layers in SoyEx and ~~distributed it to~~in deeper soil layers under MaiEx and CasEx. ~~Considering layer by layer, the significant effect of NT systems on SOC was observed in the topsoil 0–10, 0–20 and 0–40 cm in SoyEx, MaiEx, and CasEx, respectively.~~ When considering the whole profile (0–100 cm), the annual SOC accumulation ~~ve layers, all the NT systems significantly increased SOC stock across the soil profile under MaiEx and CasEx. For SoyEx, the cumulative SOC stock is restricted to 0–20 cm under NT monocropping and to 0–80 cm under NT crop rotation systems. In the whole profile (0–100 cm), the annual SOC cumulative~~ rates in NT systems ranged from 0.86–1.47~~, 0.65–1.00,~~ and 0.70–1.07 Mg C ha^{-1} yr^{-1} in MaiEx ~~, SoyEx,~~ and CasEx, respectively~~, and from 0.65–1.00 Mg C ha^{-1} yr^{-1} in. SoyEx despite insignificance.~~ Similarly, under all NT systems, ~~the impact of CA cropping systems on the~~~~an~~ increases in ~~SO~~C-POM and C-MAOM stocks were observed in the topsoil layers in MaiEx and SoyEx ~~under NT cropping systems~~ ~~whereas a significant effect on~~and in C-MAOM stock ~~in soils under CA systems was found from the surface to~~in 0–40 cm in CasEx. ~~In contrast to SOC stock, over the past 10 years,~~ However, under all the NT systems, N-POM stock ~~NT~~only increased in the surface 0–10 cm layer,~~. These systems did not increase N stock in POM and MAOM either even in the surface layer,~~ but ~~T~~N-MAOM stock decreased below 5 cm in CasEx and below 40 cm in MaiEx and SoyEx.~~it The main impact of NT systems on C-POM and C-MAOM was observed in the top 0–10 cm in MaiEx and SoyEx, whereas significant effect on C-MAOM in soils under NT systems was found from 0–40 cm in CasEx.~~

~~In contrast to SOC, N concentration and stock in NT soils only increased in the surface layer (0–5 cm). Although an increase of N-POM under NT systems was found in the top soils, a decrease was observed in the subsurface layers. Surprisingly, intensive NT systems caused the depletion of N-MAOM with significant losses observed below 5, 20, and 40 cm in CasEx, MaiEx and SoyEx, respectively. This resulted in significant N stock depletion below 40 cm and in the whole profile, particularly, under soybean and cassava NT monocropping systems.~~

Overall, our findings reveal that diachronic sampling is crucial for proper measurements of the impacts of NT systems on SOC dynamics with time. Long-term a~~A~~doption of~~ing~~ NT cropping systems accompanied by diversified crop and cover crop species~~ and high biomass C inputs with an absence of heavy soil disturbance in the long term~~ significantly increased SOC stock and ~~pools~~ fractions in the tropical red Oxisol of Cambodia. The study highlights the potential of NT cropping systems for SOC accumulation and stabilization over time, even for cassava, which is known to ~~have severe environmental impacts and~~induce soil degradation, but raises questions about soil N dynamics. Further research on the N dynamics~~N use efficiency, N cycles, and nutrient availability and their stoichiometry relationship by considering deeper layers (> 100 cm)~~ is needed to understand the mechanism driving N loss in NT systems for making informed decisions regarding sustainable soil fertility management and crop production systems.

6 Code and data availability

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All data are freely available on the CIRAD data repository https://doi.org/10.18167/DVN1/NNBBAQ (Leng et al., 2024).

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7 Author contributions

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VL co-established and managed the experiments, carried out the fieldworks, managed all sample collection campaigns and laboratory works, and wrote the first manuscript draft. FT co-managed the experiments, provided support to the team for the last 8 years and raised funds along with GDA/DALRM to sustain these long-term experiments. LT, RC, and FT conceptualized the research, supervised the field operations, analytical procedure, data computation, and reviewed the manuscript. VS, PL, LH, JS and CB gave advices for the analytical procedures, data calculation and manuscript improvement. PM significantly contributed to the implementation of the field operations, sample collection and lab works. TF performed the statistical analysis. SB raised funds, designed, established and managed the experiments during the first years and contributed to the manuscript improvement.

8 Competing interests

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One co-author is a member of the editorial board of SOIL.~~ The peer-review process was guided by an independent editor, and the authors declare that they have no competing interests to declare.~~

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