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Multicriteria assessment of recently implemented conservation agriculture cropping systems across farmers' plots in northwestern Cambodia

Sambo Pheap [a,b,*], Alexis Thoumazeau [c,d,e], Jun Murase [b], Vang Seng [f], Jean-Pierre Sarthou [g], Veng Sar [h], Linda Kimbo [h], Soklin Kheam [a], Pheakdey Chan [a], Pao Srean [j], Samrith Leang [j], Lyda Hok [k], Florent Tivet [h,i,l]

[a] Faculty of Agricultural Science, Royal University of Agriculture (RUA), Phnom Penh, Cambodia
[b] Graduate School of Bioagricultural Science, Nagoya University, Nagoya, Japan
[c] ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France
[d] CIRAD, UMR ABSys, F-34398, Montpellier, France
[e] HRPP, Kasetsart University, Bangkok, Thailand
[f] Department of Agricultural Land Resources Management (DALRM), General Directorate of Agriculture (GDA), Phnom Penh, Cambodia
[g] AgroToulouse, UMR CRBE CNRS-INP-UT3, University of Toulouse, France
[h] Cambodian Conservation Agriculture Research for Development Centre, DALRM, GDA, MAFF, Phnom Penh, Cambodia
[i] AIDA, University of Montpellier, CIRAD, Montpellier, France
[j] Faculty of Agriculture and Food Processing National University of Battambang, Cambodia
[k] Center of Excellence on Sustainable Agricultural Intensification and Nutrition, Faculty of Agricultural Education and Communications, RUA, Cambodia
[l] CIRAD, UPR AIDA, Phnom Penh, Cambodia

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ABSTRACT

Soil fertility depletion is a major challenge for annual rainfed cropping systems in the northwestern region of Cambodia which has recently undergone rapid agrarian changes. On-farm impacts of conventional tillage and Conservation Agriculture-based practices (CT and CA respectively) of maize cultivation on soil health along with agronomic and economic performances were compared. The experiment was set up in 2020 comparing CT and CA with one cover crop (CAS) and CA with a mix of three cover crops (CAM). Soil health was assessed at the end of the cropping cycle using Biofunctool®. Agronomic performances including cover crops and a cash crop (maize) along with intermediate consumption were recorded in 2021 and 2022. Selected components of soil health, agronomic and economic performances were used for multi-criteria analysis. On this Mollisols, SHI was positively impacted under CA (15% and 6% higher in 2021 and 2022), but with some soil parameters varied from one year to the next. In 2021, lower plant density ($p < 0.05$) was recorded under CA, highlighting the need to improve the efficiency of no-till sowing methods. Intermediate consumption was not significant between the treatments for both years. Non-significant difference in yields was recorded under the three treatments in both years, but while both CA systems remained stable, CT dropped by 10% in 2022 with some differences for yield components with a larger number of grains per column and higher mass of grains under CAS. Gross value added under CA was 12.7% less than CT in 2021, it surpassed CT by 43% in 2022. Agronomic and economic performances were still unstable at this early stage of implementation with wide variability across the two cropping seasons emphasizing that with this soil type, CA induced a significant increase in soil health but did not yet lead to significant increase in productivity or economic outcomes.

1. Introduction

Over the last two decades, northwestern Cambodia has faced key land transformations from forest to arable land. The trend mainly began in 1998 at the end of the Khmer Rouge period with in-migration to the northwestern regions to improve household living standards while simultaneously meeting the demand for boom crops (mainly maize and cassava) on regional markets (Kong et al., 2019). First, staple crops and

* Corresponding author. Faculty of Agricultural Science, Royal University of Agriculture (RUA), Phnom Penh, Cambodia.
E-mail address: psambo@rua.edu.kh (S. Pheap).

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cash crops (i.e., peanut, sesame, soybean) were cultivated during the early stages of forest clearance. Subsequently, when the roads were rehabilitated and access to markets became easier, smallholder farmers shifted in to grow maize or cassava for a better cash return (Kong et al., 2021). The rapid expansion of agricultural land led to key environmental issues. Nut et al. (2021) highlighted significant soil erosion over a very short period of time (1.9 million t yr^{-1} and this process increased by 236% in 2015 and Bai et al. (2008) estimated that soil was already 43% degraded at national scale, which could affect at least 25% of the population in Cambodia. In addition to changes in land use, the rapid boom in cash crops in the region combined with increased soil disturbance due to continuous tillage-based management led to a progressive decline in soil fertility as well as in yields and the appearance of visual symptoms of nutrient deficiencies, such as N and P in crops (Guppy et al., 2017).

Conservation agriculture (CA) was proposed in northwestern Cambodia as a way of limiting and potentially reversing the loss of soil fertility, while maintaining yield and profits. CA management practices are based on three pillars: minimizing soil disturbance, maintaining a permanent soil cover by planting cover crops in addition to the cash crop, and diversifying the crops grown in the system to improve both soil quality and the yield of annual crops (Hobbs et al., 2007). When fully implemented, CA has already proved to be efficient in improving soil health in a variety of contexts. CA improves the abundance, diversity and function of soil biota (Nunes et al., 2020), increases SOC and nitrogen stocks (Bohoussou et al., 2022), minimizes soil lost through wind and water erosion (Van Pelt et al., 2017), improves the soil structure and increases the pool of nutrients (Zhang et al., 2021), enhances soil hydraulic properties (Basche and DeLonge, 2019; Eze et al., 2020), increases crop resilience to climate change by increasing organic carbon stocks (Powlson et al., 2016; Nicoloso and Rice, 2021), and enhances crop productivity in the case of rainfed agriculture (Pittelkow et al., 2015). Although CA has positive impacts, a range of challenges can limit its adaptability to different contexts and hence its rate of adoption varies by local farmers. In most cases, the reasons given for low adoption rates emphasize financial issues (Knowler and Bradshaw, 2007; Brown et al., 2017), farmers' lack of knowledge and lack of technical support (Knowler and Bradshaw, 2007) along with farmers' lack of access to new means of production (no-till planter, seeds of cover crops, etc.). The benefits of CA-based systems largely derive from the diversity of plants used (i.e., main crops and cover crops) and the quantity and quality of biomass returned to the soil, but the soil and the climatic context can also deeply affect the performance of CA (Su et al., 2021) and studies with primary results remain scarce in South East Asian contexts.

The few studies that have been conducted, including those by Hok et al. (2015), Pheap et al. (2019), and Masson et al. (2022), highlighted the positive impacts of CA-based cropping systems, i.e. increased SOC and labile-C pool contents in the top soil, increased water infiltration, improved soil structure, and reduced incidence of plant-parasitic nematodes in the Cambodian context. A recent study also reported a rapid improvement in soil carbon dynamics under CA management in Mollisols (Koun et al., 2023). The performance of maize under CA has also been evaluated in various contexts and many authors reported positive impacts of such practices on maize yield (Rusinamhodzi et al., 2011; Thierfelder et al., 2015; Jat et al., 2020), where the greatest effects were observed under long-term CA management (Thierfelder and Mhlanga, 2022). However, agronomic performances need to be contextualized and other internal and external factors of the farms need to be taken into account to fully understand the performances of CA cropping systems (Giller et al., 2009; Mafongoya et al., 2016). In northwestern Cambodia, the price volatility of the different boom crops and the increase in the market price of cassava limited the long-term adoption of CA-based maize cropping systems (Kong et al., 2021). The stable and improved outputs of CA systems expected in the long run were consequently reduced. Understanding the performances of short-term implementation of CA thus also seems critical in a context of rapid changes (Koun et al., 2023). Despite the numerous reports of the long-term benefits of CA for soil health (Rusinamhodzi et al., 2011), studies conducted during the early stages of CA implementation are still rare, particularly in South-East Asia where the adoption of CA systems is still in its infancy.

Multicriteria assessment of cropping systems is a key to understanding their sustainability and potential adoption by farmers. This approach consists of combining the assessment of environmental, economic and social components and identifying their tradeoffs. Considering ecological-economic trade-offs is indispensable if biodiversity is to be integrated into agricultural production, yet these components have rarely been analysed together (Rosa-Schleich et al., 2019). Multicriteria assessment frameworks have already been shown to be of interest for CA and many studies focused on one of the three main pillars of CA, but few have assessed the multi-criteria performances of the combined pillars of CA (Adeux et al., 2022). Craheix et al. (2016) showed positive interactions between key elements of CA that enable more sustainable performances of such systems.

The aim of this study was to find out whether soil health, agronomic and economic outcomes of maize production would be improved in the second and third year of transition from CT to CA. We hypothesised that the three components would be significantly improved in CA compared to CT in both the second and third year of CA implementation.

2. Materials and methods

2.1. Study site

The experiment was conducted in farmers plots around Reaksmey Sangha village (12°55′59.7"N 102°50′38.4"E, 137m ± 14 a.s.l.), Rattanak Mondul district, Battambang province, Cambodia. These areas were cultivated following forest clearance between 2005 and 2010. The fields were later converted to annual cropping systems (mostly maize and cassava). In the study region, most rain usually falls during the monsoon from May to November. Nonetheless, rainfall is unevenly distributed across the seasons and average rainfall was 1366 mm per year in the period 1982 to 2021. The average annual temperature at the study site is 27.7 °C. The soil is known as Kampong Siem in Khmer (White et al., 1997) or Phaeozem (WRB) (IUSS Working Group WRB, 2022) comprising 52% of clay, 32% of silt and 16% of sand, mean pH (H_2O) is 7.3 (range 6.34–8.03), SOC: 26 g kg^{-1} and bulk density of 1.06 g cm^{-3} in the 0–10 cm soil layer and the fields have average slope of 4.7% (Koun et al., 2023).

2.1.1. Experimental design

The on-farm experimental design is described in detail in Koun et al. (2023). Briefly, the experiment was implemented in 2020 and initially comprised a network of seven farmer's plots, among which six plots that were studied in both 2021 and 2022 were included in the present study. Three management practices (hereafter treatments) were tested in a 1-ha area per plot. The three treatments were randomly distributed in each plot: (1) CT: conventional tillage-based maize (*Zea mays* L.); (2) CAS: maize-based conservation agriculture (CA) with direct seeding of maize on a standing green cover crop of sunnhemp (*Crotalaria juncea* L.), and (3) CAM: maize-based CA with direct seeding of maize on mixed cover crops consisting of sunnhemp + pearl millet (*Pennisetum glaucum* L.) + cowpea (*Vigna unguiculata* L.). The three treatments were implemented and managed by the farmers themselves, with technical support provided by the team from the Cambodian Conservation Agriculture Research for Development Center (CARDEC) from the Department of Agricultural Land Resources Management (DALRM), General Directorate of Agriculture (GDA).

2.1.2. Management practices

The management practices of each treatment remained the same over the three consecutive years, from 2020 to 2022. Details of the farm management calendar are given in Koun et al. (2023). Under CT, the field was ploughed twice, the first time a few months after the maize was harvested in early January and the second time the plot was ploughed to a depth of 15–20 cm with a six-disc plow before the maize was sown. Under CAS and CAM, the cover crops were sown using a no-till planter (Vence Tudo Planter, PA 5000) prior to maize sowing at a rate of 30 kg ha^{-1} *C. juncea* L. in CAS and a mixture of 20 kg ha^{-1} *C. juncea* L., 10 kg ha^{-1} *P. glaucum* L. and 25 kg ha^{-1} *V. unguiculata* L. in CAM with no additional input of fertilizer or weeding during the growing period. Forty-two days after sowing (DSA) in 2021 and 47 days after sowing in 2022, the cover crops were terminated using a roller crimper mounted in front of the tractor. The average aboveground inputs supplied by the dry biomass of the cover crops were recorded (Table 1). Weed biomass was not recorded under CT management.

Maize was sown at the same time in all three treatments using a no-till planter targeting a plant density at sowing of 80,000 seeds with 60 cm inter-row spacing. Basal fertilizer was applied below the sowing line in the form of 100 kg ha^{-1} of diammonium phosphate (DAP, NPK: 18-46-0) and 50 kg ha^{-1} of potassium chloride (KCl, NPK: 0-0-60). An additional 50 kg ha^{-1} of urea (NPK: 46-0-0) was broadcasted 20 days after sowing (DAS) and then 35 DAS.

Weeds were controlled by applying glyphosate herbicide (average 1.77 l ha^{-1} at 480 g l^{-1}) with 2-4-D (0.5 l ha^{-1} at 720 g l^{-1}) in all plots and treatments after sowing maize. Weed control during the maize development stage varied from one plot to another; however, the most common method was applying mesotrione herbicides 20 DAS of maize. Emamectin (1.0 l ha^{-1}) was applied to control fall armyworms (*Spodoptera frugiperda*) 15 DAS of maize. Maize ears were harvested at the end of November and under all treatments, the remaining biomass was left on the ground in the fields. The average inputs of aboveground dry biomass from maize were recorded (Table 1).

In 2021, only cover crops were sown before the main crop under CAS and CAM as in 2020 (Koun et al., 2023). In 2022, due to sufficient rainfall in late March the farmers decided to sow mungbean (*Vigna radiata* L.), a pulse crop grown for its grains, under all the treatments. However, because its yield was low, the farmers decided not to harvest mungbean (Table 1), due to the high cost of labor for harvesting and low market price for mungbean at that time. All the mungbean biomass and grains were thus left in the fields. Under CT, the mungbean was considered as green manure, and under CAS and CAM, the cover crops were sown on top of the mungbean biomass.

2.1.3. Meteorological conditions and management

Annual rainfall in 2021 was 1118 mm and in 2022, it was 1660 mm (Supplementary Material 1). During the growing period of the cover crops and the cash crop from May to August 2022, the fields received better rainfall (about 160 mm per month) which resulted in homogenous growth of cover crops and maize, whereas in 2021, average rainfall in the same period was only 110 mm per month. However, from September to November 2022, the cumulative rainfall was excessive (958 mm) and led to excessively saturated soils that remained saturated for a long time (Supplementary Material 1).

2.2. Data collection

Soil, agronomic and economic performances were assessed in the six study plots simultaneously in 2021 and 2022.

2.2.1. Soil health assessment

Soil health was assessed in the top 10 cm of soil after harvest. Five intra replicates per treatment per plot were collected at the end of the cropping cycle in November. In 2021, all measurements were taken in one week whereas in 2022, 2.5 weeks were needed to take all the measurements, due to heavy rainfall. The measurements were taken in one plot after another, while the choice of treatment in each plot during one field campaign was randomly selected. Then five composites were taken, mixed before fresh sieving through 5 mm sieve. The sieved soil samples were weighed 100g for SituResp® and 50g for nutrient analysis. The same soil samples were taken back to RUA for further assessment of moisture content, permanganate oxidable organic carbon (POXC)", available phosphorous and exchangeable potassium.

To assess soil health, we applied the Biofunctool® approach (Thoumazeau et al., 2019a). Briefly, we used soil indicators linked to three soil functions: carbon transformation, nutrient cycling and soil structure maintenance. Four indicators were used for the carbon transformation function: first, we measured the pool of labile carbon with permanganate oxidizable carbon (POXC)(Weil et al., 2003). Briefly, 2 mL of 0.2 M $KMnO_4$ solution was agitated with 2.5 g of soil at the Royal University of Cambodia laboratory in Phnom Penh. Lamina sticks were filled with a substrate provided by Terra Protecta company, and was used to assess soil meso fauna activities within 2 weeks of incubation in the field (von Törne, 1990). Soil basal respiration (SituResp®) was measured in the field following the procedure of Thoumazeau et al. (2017) and earthworm activity was estimated by quantifying the dry biomass of casts located within a 25 cm × 25 cm square marked on the soil surface (Cast) (Thoumazeau et al., 2019a). For nutrient cycling function, mineral nitrogen (NO_3^- and NH_4^+), 50g of fresh soil (passed through 5 mm sieve) was placed in a bottle containing 180 ml of 1M KCl solution. The bottle was then stirred at 200 rpm for 90 min before being filtered to get a clear solution The filtrate was then used to measure soil available nitrate (NO_3^--N) and ammonium (NH_4^+-N) (NF-ISO 14256-2, 2000). Available P were adapted from (FAO, 2021). 5.0g of soil (passed through 0.5 mm sieve) were added in the extracting solution, filtered and then were used for measurement with a Spectrophotometer at 882 nm. Exchangeable K were analysed by extracting 2.50g of soil (passed through 2.0 mm sieve) with 1M ammonium acetate, filtered and tested directly with a Flame photometer (Black, 1965). For the structure maintenance function, we assessed the soil aggregate stability at two different depths (AggSurf, 0–5

Table 1
Aboveground dry biomass input (mean value ± std. error) of cover crops and maize per year. CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *Crotalaria juncea* (sunnhemp), and CAM-maize under conservation agriculture with mixed cover crops (sunnhemp + cowpea + pearl millet).

Treament	Year	Aboveground biomass of mungbean ($t\ ha^{-1}$)	Aboveground biomass of cover crops ($t\ ha^{-1}$)	Aboveground biomass of maize ($t\ ha^{-1}$)	Cumulative aboveground biomass ($t\ ha^{-1}$)
CT	2021	–	–	4.44 (±0.17)	4.44 (±0.17)
CAS	2021	–	6.74 (±0.13)	4.34 (±0.14)	11.08 (±0.19)
CAM	2021	–	6.12 (±0.09) *(Sunnhemp 45.6%; Pearl millet 42.6%; Cowpea 11.8%)* [a]	4.90 (±0.11)	11.01 (±0.15)
CT	2022	1.52 (±0.07)	–	4.55 (±0.15)	6.06 (±0.13)
CAS	2022	1.55 (±0.10)	5.51 (±0.22)	4.27 (±0.11)	11.34 (±0.22)
CAM	2022	1.53 (±0.10)	4.32 (±0.13) *(Sunnhemp 42.9%; Pearl millet 43.3%; Cowpea 13.9%)*	3.95 (±0.10)	9.80 (±0.19)

[a] The percentage between brackets indicates the percentage of biomass produced by each cover crop species in the total biomass.

cm) and (AggSoil, 5–10 cm) using the method proposed by (Herrick et al., 2001). We then made an evaluation of the soil structure by Visual evaluation of soil structure (VESS) (Guimarães et al., 2011)).

2.2.2. Agronomic performances

At maturity, agronomic data were collected for each treatment and in each plot. Five sub-samples were assessed for each treatment. First, in an area of 9.6 m^2 (4 rows of maize with 0.6-m inter-row spacing × 4 m in length) per sub-sample, we recorded the number of plants, the percentage of plants that produced ears, and number of ears per plant. The aboveground biomass (excluding ears) of the plants was weighed and a sub-sample was oven dried at 75 °C for 72 h to calculate the dry mass of the maize residues (t ha^{-1}). The fresh mass of ears was weighed per sub-sample, after which the fresh mass of the kernels in 10 kg of ears was recorded. Grain moisture was recorded using a Multiple Moisture Tester (model PM-390) and grain yield was then calculated at 14% moisture content. Second, on an adjacent area and using 5 sub-replicates per treatment, the number of ears in one 2-m long sowing line (1.2 m^2) was recorded to assess the yield components including the number of rows per ear, the number of grains per row and the mass of grains at 14% moisture.

2.2.3. Economic performances

All field operations and related expenses were recorded in collaboration with the farmers on each plot and for each treatment. We focused on (i) intermediate consumption (IC) representing the cost of inputs, goods and services used throughout the production cycle, such as seeds, fertilizer, pesticides, ploughing, sowing services, (ii) gross product (GP), (iii) gross value added (GVA = GP - IC), and (iv) labor productivity which was adapted from Dayet et al. (2024).

Before the maize cycle, IC costs covered the period from the last maize harvest until termination of the cover crops under CAS and CAM. Costs under CT only concerned ploughing and weeding. Under CA, this period involved the cost of cover crop management including the cost of cover crop seeds, sowing, rolling and termination. In 2022, a mungbean cycle was added during this period and although it was not harvested, all the expenses (e.g., seeds, sowing, weed and pest management, and labor) applied and were recorded for CT and CA. During the maize cycle, the expenses were divided into sowing, fertilizer, pest and weed management, harvest, and transportation. Sowing costs covered the purchase of maize seeds and sowing service. Costs of fertilizers include all the fertilizers used from basal to top dressing. Pest and weed management costs include the costs of pesticides used to control both pests and the weeds that grow during the maize growing period. Harvest and transportation costs include the cost of contractors who harvest the maize ears and transport them to local buyers.

Gross product (GP) was calculated by multiplying the yield per ha by the actual market price of the yield. The farm gate price for grains (that dried on the plants in the field) varied significantly from US\$ 250 t^{-1} in 2021 to US\$ 325 t^{-1} in 2022. The difference in the farm-gate price between 2021 and 2022 is due to the decrease in the area under maize in neighbouring countries (i.e., Laos, Vietnam and Thailand), with a higher selling price of maize in 2022 than in 2021 and the previous 5 years (FEWS NET, 2023, World Bank, 2023). Large fluctuations can be observed from year to year depending on regional demand, bearing in mind that several commodities (e.g., maize, cassava, cashew nuts, pepper …) produced in Cambodia are traded to neighbouring countries, especially Thailand for maize. In addition, the recovery of pig production after the African swine outbreak in 2022 and of poultry production have also boosted the demand for feed maize and the increase in the farm gate price from the end of 2022 and along the first half of 2023 (USDA, 2024). We then calculated the Gross Value Added (GVA) as the difference between the GP and the IC. We also measured the labor used for crop production (family and hired labor), from the beginning to the end of the crop cycle and quantified the labor productivity calculated as the GVA man-day^{-1} of labor required for the crop considering one man-day to be 8 h.

2.3. Data analysis

All data were analysed using R software (R Development Core Team, 2008; Version 4.3.1). We first performed descriptive analyses. Few outliers were recorded for the soil analysis, they were considered as such (<5% of the data set per variable) when one maximum among the five sub-replicates deeply out-ranged the others. For univariate analysis, we analysed the effects of management practices on the different variables in the two cropping years. Before implementing the tests, we checked the normality and homoscedasticity assumptions were valid. For soil health and agronomic data, we implemented a mixed linear model test, and integrated the nested design (replicates/intra replicates) as a random effect. For economic data, ANOVA was used. When a significant effect was found, we applied a post-hoc test. In the few cases where the preliminary assumptions were not confirmed, we applied a non-parametric Kruskall-Wallis test.

For soil health analysis, the results were aggregated using principal component analysis (FactoMineR package (Lê et al., 2008). In the PCA, weights were assigned to each indicator so as to consider each of the three soil functions equally (Pheap et al., 2019). The coordinates of individuals on dimensions with an eigen value > 1 were used to construct the soil health index according to equation (1) and equation (2) (Obriot et al., 2016; Thoumazeau et al., 2019b).

$$Wi = \sum_{j=1}^{p} \lambda j \times fj \quad (1)$$

$$SQI = \sum_{i=1}^{n} Si \times Wi \quad (2)$$

Wi are weighted factors calculated from the relative percentage of total variability to each principal component of the PCA (*fj*) and the sum of squared coordinates on each eigenvector (λj) and *Si* are the normalized indicator scores. For the normalization, high scores were assumed to reflect better soil health for each indicator, with the exception of the soil structure indicator (VESS) as this soil structure indicator gives a higher score for not optimal soil conditions (score 5 = very compacted, less aeration, less aggregation, very few or no root penetration). For VESS, we used “the lower the better” scoring function Thoumazeau et al. (2019b). Once the soil health index was calculated, ANOVA followed by Tukey post-hoc tests were performed on the total scores and scores per soil function (carbon transformation, nutrient cycling, structure maintenance). The multicriteria analysis was made through radar chat of the selected components: (1) Economic components—Intermediate consumption, Gross Product, Gross Value Added, Total Labor and Labor Productivity; (2) Soil health—Carbon Transformation, Structure Maintenance and Nutrient Cycling; (3) Agronomic performance—Aboveground Biomass, and Grain Yield. Values for each selected variable were normalized between 0 and 1, by: each value subtracted minimum then divided by maximum subtracted minimum value of the variable. For all parameters, except Total labor and Intermediate consumption the higher value was associated with the better performance.

2.4. Soil health

Significant differences in carbon transformation were observed between conventional tillage-based agriculture (CT) and the different forms of conservation agriculture (both CA systems) in the two years (Table 2). The differences applied to basal soil respiration (SituResp®), labile carbon (POXC) and cast density. Only the Lamina indicator was not sensitive to treatments in either year. The values under CT were significantly lower than under CAs. CAM often outperformed CT, even though differences in POXC and Cast were not statistically significant in 2022. POXC and SituResp® values were generally higher in 2021 than in 2022. Effects on nutrient cycling impacts were less clear (Table 2), with no significant

Table 2
Biofunctool® indicators per treatment (mean value ± std. error (SE)). CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *Crotalaria juncea* (sunhemp), and CAM-maize under conservation agriculture with mixed cover crops (sunhemp + cowpea + pearl millet).

Treatment	Year	Carbon transformation				Nutrient cycling				Structure maintenance		
		SituResp® (Abs difference)	POXC (mg C kg^{-1})	Lamina (% substrate)	Cast (t ha^{-1})	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	AvP (mg kg^{-1})	ExK (mg kg^{-1})	VESS (Score)	AggSurf[a] (Score)	AggSoil (Score)
CT	2021	0.46 (±0.05) b	733.2 (±16.2) b	57.85 (±2.99)	4.47 (±0.40) b	17.11 (±1.82)	8.09 (±0.48) b	41.8 (±3.6)	255.8 (±16.3) b	3.08 (±0.13)	5.52 (±0.06) b	5.66 (±0.06) b
CAS	2021	0.60 (±0.04) a	803.1 (±19.4) a	57.59 (±4.70)	38.70 (±3.49) a	17.18 (±3.16)	15.94 (±2.10) a	47.1 (±3.6)	386.1 (±31.6) a	2.85 (±0.08)	5.84 (±0.03) a	5.74 (±0.05) ab
CAM	2021	0.60 (±0.04) a	791.7 (±17.0) a	60.75 (±4.00)	30.58 (±3.19) a	15.94 (±1.82)	9.73 (±0.45) b	43.7 (±3.7)	304.2 (±14.2) a	2.88 (±0.09)	5.93 (±0.02) a	5.85 (±0.04) a
CT	2022	0.14 (±0.03) b	659.5 (±14.6) b	45.65 (±4.63)	29.63 (±2.03) b	1.49 (±0.18)	12.95 (±0.78)	63.7 (±2.9)	247.0 (±19.9) b	3.43 (±0.10)	5.65 (±0.07) b	5.74 (±0.07)
CAS	2022	0.30 (±0.04) a	737.3 (±21.1) a	46.77 (±3.57)	35.48 (±2.84) a	1.54 (±0.23)	12.94 (±0.62)	58.7 (±3.1)	283.0 (±25.9) a	3.40 (±0.08)	5.93 (±0.01) a	5.84 (±0.04)
CAM	2022	0.29 (±0.04) a	713.2 (±17.7) ab	44.81 (±4.25)	33.28 (±2.68) ab	1.15 (±0.18)	14.10 (±0.73)	60.4 (±4.4)	292.4 (±16.9) a	3.20 (±0.09)	5.90 (±0.03) a	5.87 (±0.02)

** Different letters indicate difference among treatments at $p < 0.05$.
*** Indicators without letters were non-significant difference at $p > 0.05$.
[a] In 2022, this indicator was analysed using a non-parametric method.

differences in nitrate or available phosphorus between treatments in both years. However, ammonium levels were significantly higher in 2021 on CAM soils when compared to CAS. Although non-significant, nitrate levels were always lower under CAM when compared with CT and CAS. Exchangeable potassium was significantly higher in CA systems in 2021 and under CAS in 2022 than under CT. Regarding structure maintenance, VESS was not affected by treatments in either year, but tended to be higher in 2022 than in 2021 (Table 2). Regardless of the year, the AggSurf under both CA systems was significantly better than under CT. However, the AggSoil was only significantly different in 2021 with higher values under CAM as compared to CT. Fig. 1 depicts the results of the multivariate analysis of the 11 soil health indicators. The two dimensions of PCA explained 57% of dataset variability in 2021, which was relatively higher than in 2022 (43%). In 2021, CT was clearly distinguished to both CA systems mainly driven by VESS, AggSurf, soil respiration cast and NH_4^+-N. In 2022, the difference between CT and CA treatments is less obvious and is driven by AggSurf and AggSoil. The aggregated soil health index (SHI) shows that, both in 2021 and 2022, the CA score was significantly higher than CT (Fig. 2). In 2021, higher values ($p < 0.05$) of carbon transformation and structure maintenance functions were recorded under both CA systems when compared with CT. In 2022, the differences of SHI between both CA systems and CT resulted from different trends in carbon transformation and structure maintenance, but these two functions were not significantly different from both CA systems to CT.

2.5. Agronomic performances

Plant density was lower in 2021 than in 2022 (Table 3). In 2021, the total number of plants per hectare under CT (55,972 plants ha^{-1}) was 21% higher than under CAS and 12% higher than under CAM. In 2022, the difference between CT (64,340 plants ha^{-1}) and CAS and CAM were reduced to only 7% and 9%, respectively. Despite different plant densities in the two years, the ability to produce ears in all treatments did not differ significantly, higher than 90% in all cases. The number of rows per ear was significantly higher (13.3 rows) under CAS when compared with CT and CAM. In 2002, the number of rows was higher than 14 in all treatments and no differences were found between treatments. In 2021, the number of grains per row was significantly higher under CAS (36.25) than under CT and CAM. In 2022, fewer grains were recorded under CT ($p < 0.05$, 29.67) than under CAS and CAM. In 2021, grain mass differed in the three treatments with the lowest values under CT, representing an increase of 29.4% and 45.4% under CAM and CAS, respectively. In 2021, differences in grain yields among the treatments were not significant with an average yield of 5.25 tons ha^{-1}. In 2022, there was no significant difference in 1000-grain mass but total grain yields were higher under both forms of CA than under CT and increased by 10.9%–14.3% under CAM and CAS, respectively. This was reflected in lower yields under CT in 2022 compared to 2021.

2.6. Economic results

The intermediate consumption (IC) and the gross product (GP) did not differ from one treatment to another. However, IC and GP were much higher in 2022 than in 2021 due to the increase of fertilizers, seed, pesticides and services contributing to higher IC along with a higher on-farm gate price in 2022 (2021 = US$250/ton of grain and 2022 = US$325/ton of grain) that generated higher GP (Table 4).

The main differences in intermediate consumption were linked to the cover crop period prior to the sowing of maize, with an average contribution to the IC of US$116 ha^{-1} and US$164.7 ha^{-1} in 2021 and 2022, respectively in the two CA systems (Table 4). The other IC component did not differ significantly under the three treatments. Total IC increased between 2021 and 2022. The main contributing factor was the cost of the seeds of the maize hybrid that was used. In 2022, sowing costs were 39% higher under CT and 20% higher under both CA systems compared to in

2021. In 2022, mungbean was sown in all the plots and IC under CT was 16.7% higher ($p < 0.05$) than both CA systems (Table 4). There were no significant differences in fertilizer costs in all treatments between the two crop cycles, but the costs in 2022 were 23.6% higher due to the increase of fertilizer costs in the market. No significant differences in IC between the treatments were observed for pest control, harvest and transport and with the exception in 2021 of higher IC of weed management under both CA systems.

Under CT, the gross value added in 2021 was significantly higher than under CAS but did not differ significantly from that of CAM. both CA systems and CT exhibited different patterns in 2021 and 2022, with an increase (+13%) in gross value added under both CA systems and a decrease (−24%) under CT.

In both years, despite non-significant effects, labor productivity was lower in CT compared to both CA systems due to higher labor requirement for weed management. Due to the amplitude of the gross value added between years, labor productivity in CT in 2022 decreased by 51% as compared to 2021, while in both CA systems were stable in both years was observed in 2022. However, labor productivity under CAS was slightly increased while in CAM labor productivity was marginally reduced.

2.7. Multicriteria

Combining the results of a multicriteria assessment, we observed different patterns in 2021 and 2022 (Fig. 3). In 2021, the patterns of the different components of the agroecosystem varied. Regarding soil health, both CA systems outperformed CT, while lower values were recorded for Gross Product (GP), Gross Values Added (GVA), and labor productivity. In 2022 and for all criteria, both CA systems shown better values than CT, and no clear distinction was evident between CAS and CAM.

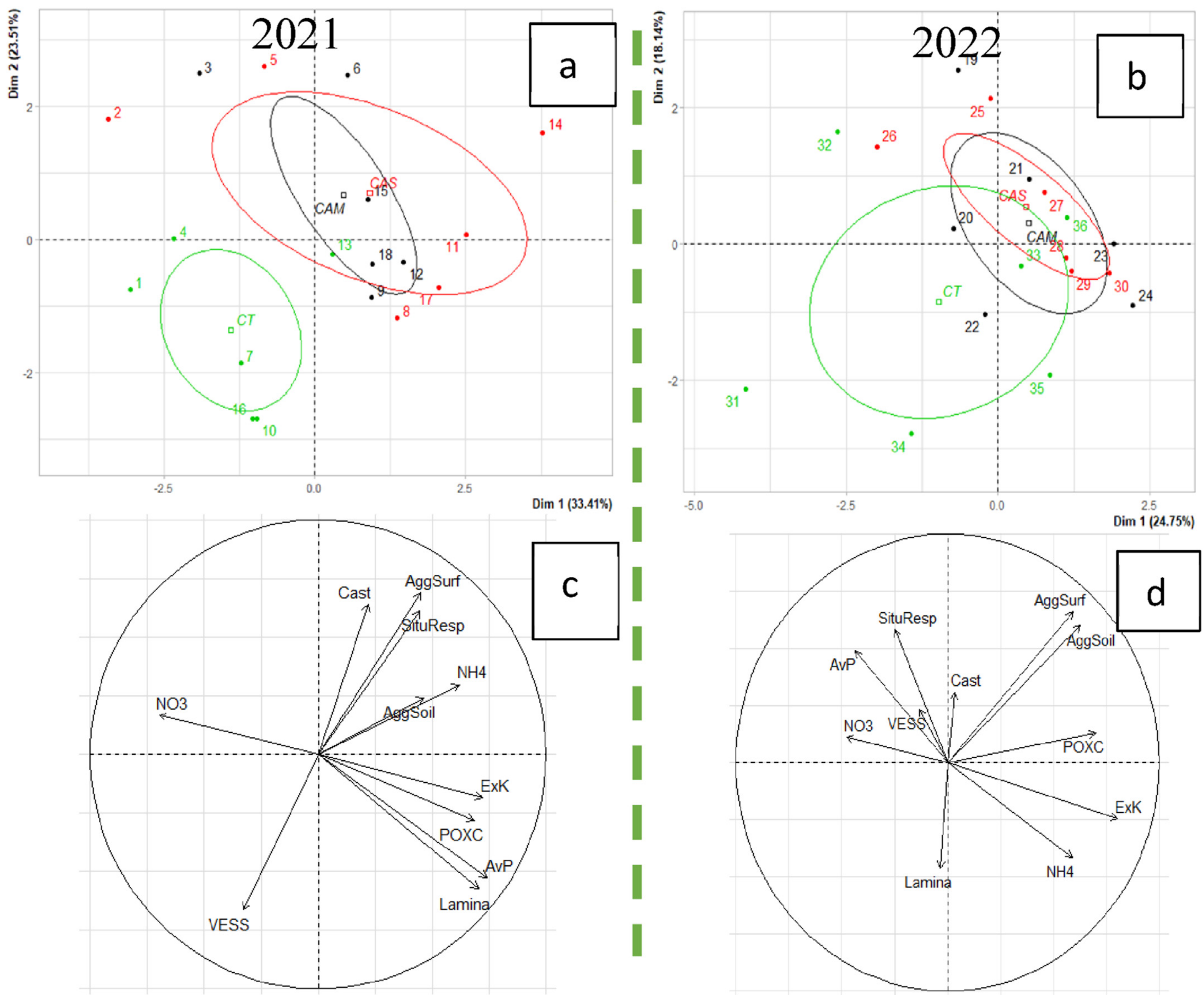

Fig. 1. Principal component analysis (PCA) of the impact of agricultural practices and management on soil health in 2021(a) and 2022 (b) cropping cycles. Each number in both (a) and (b) represents all parameters contributes to PCA of each treatment. CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *C. juncea* (sunnhemp) as cover crop prior to sowing maize, and CAM-maize under conservation agriculture with mixed cover crops (sunnhemp + cowpea + pearl millet). Top: graphs of individual treatment. Bottom: correlation circle showing all indicators in 2021 (c) and 2022 (d).

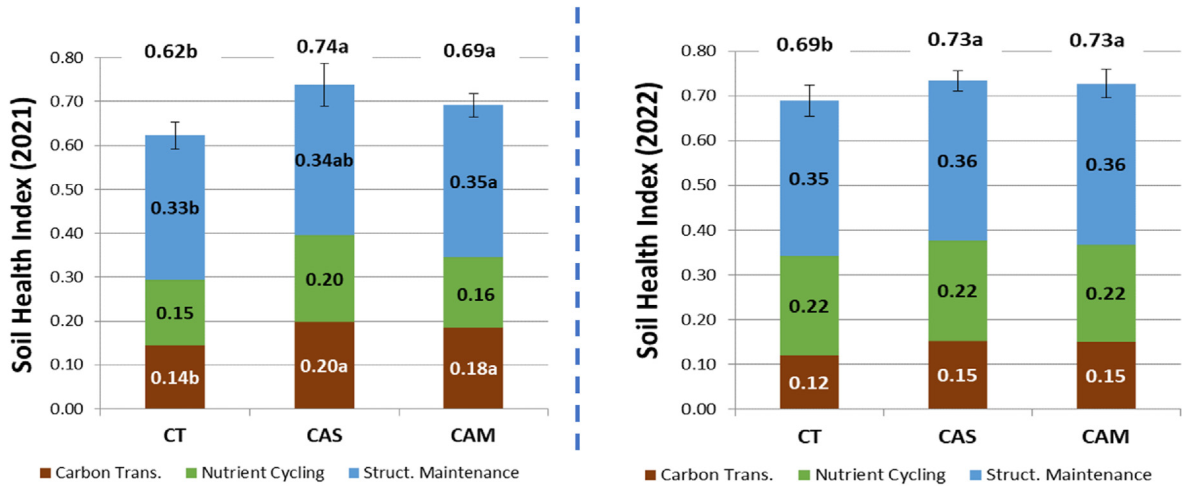

Fig. 2. Soil health index (SHI) per treatment in 2021 and 2022. CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *C. juncea* (sunnhemp), and CAM-maize under conservation agriculture with mixed cover crops (sunnhemp + cowpea + pearl millet).

Table 3
Agronomic data of cropping cycles in 2021 and 2022 (mean value ± std. error (SE)). CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *Crotalaria juncea* (sunnhemp) before maize, and CAM-maize under conservation agriculture with mixed cover crops (sunnhemp + cowpea + pearl millet) before maize.

Treatment	Year	Agronomic characteristics		Ear and grain attributes			Production attributes	
		Plant population	Ears produced	Row per ear[a]	Grain per column[a]	1000 grain	Shoot dry matter	Grain Yield
		plants ha^{-1}	%	number	number	(g at 14%)	tons ha^{-1}	(tons ha^{-1}, at 14%)
CT	2021	59167 (±4576) a	94.6 (±0.6)	12.73 (±0.23)	32.03 (±1.86) ab	193.0 (±6.27) b	4.44 (±0.57)	5.38 (±0.21)
CAS	2021	47017 (±1572) b	94.1 (±1.5)	13.26 (±0.30)	36.25 (±1.16) a	280.6 (±26.28) a	4.45 (±0.31)	5.05 (±0.17)
CAM	2021	52604 (±2795) ab	93.9 (±0.9)	12.83 (±0.26)	30.41 (±1.30) b	249.7 (±22.02) a	4.89 (±0.22)	5.32 (±0.16)
CT	2022	64340 (±2808)	92.3 (±1.8)	14.82 (±0.17)	29.67 (±1.11)	247.7 (±10.0)	4.54 (±0.5)	4.81 (±0.38)
CAS	2022	60035 (±2854)	91.7 (±1.5)	14.47 (±0.27)	31.94 (±1.35)	251.0 (±9.0)	4.26 (±0.37)	5.50 (±0.05)
CAM	2022	58368 (±829)	90.7 (±1.8)	14.15 (±0.20)	32.42 (±0.83)	257.2 (±7.1)	3.95 (±0.36)	5.22 (±0.27)

** Different letters indicate difference among treatments at $p < 0.05$.
*** Indicators without letters were non-significant difference at $p > 0.05$.
[a] non-parametric data analysis in 2021 and 2022. Yield components come from one sowing line 2 m in length; and total yield is from a 9.6 m^2 area.

3. Discussion

3.1. Does conservation agriculture perform better than conventional tillage-based agriculture after 2–3 years?

This study combined different methods to better understand how conservation agriculture affects the trade-offs between system components and performances. Soil improvement is a key objective of conservation agriculture practices. Under our conditions, some soil parameters were already sensitive to management practices especially POXC and SituResp®, as highlighted previously by Koun et al. (2023) in a study on an earlier crop cycle conducted at the same site. The significant decrease of the soil disturbance and enhanced carbon inputs resulting from the provision of both aboveground and belowground biomass through cover crops have notably enhanced this carbon fraction (POXC), which are known to be responsive to management practices(Bongiorno et al., 2019). Earthworm cast density and soil exchangeable potassium were also higher under CA systems than under CT. These results are in accordance with those of several studies emphasizing a common trait under no-till cropping systems with higher abundance of earthworms under no-till cropping systems (Corsi and Muminjanov, 2019; Stagnari et al., 2020; Cárceles Rodríguez et al., 2022; Jat et al., 2022). In our study, this increase in earthworm density, measured only using castings harvested on the surface of the soil, is a positive sign, given the multi-functional role of these ecosystem engineers in fragmenting and decomposing organic matter, stabilizing SOC within biogenic structure, increasing nutrient cycling and water infiltration, among other benefits (Blouin et al., 2013). Regarding all the other parameters, despite trends, differences were not significant, nor sensitive to the year the measurements were made. With the exception of AggSoil in 2021, when it came to parameters where a significant difference was recorded, CAS outperformed ($p < 0.05$) CT, along with higher values when compared with CAM (Table 2). These results regarding CAS and CAM were somewhat counter-intuitive, as one might expect these indicators to be improved on the basis of systems built around a wider range of plant diversity (CAM). In other contexts and for a longer experiment, results showed a more significant impact on all the Biofunctool® indicators on soil health index (Pheap et al., 2019; Kulagowski et al., 2021a). One of the hypotheses is that CA takes more than three years to establish (Prairie et al., 2023). This may be particularly true in the case of Mollisols which have intrinsically higher soil carbon content, better soil structure, better agricultural potential than other types of soil (Liu et al., 2012) and may thus be less sensitive to a change in practices at the early stage. However, even in the case of soils with high agronomic potential like Mollisols, inadequate agricultural management results in degraded soil functions (Liu et al., 2012). Wang et al. (2023) highlighted for Mollisols loss of soil function linked to erosion rates and to the position of different land uses in an agricultural toposequence.

The difference in plant density between CT and CA was mainly due to difference in seed-to-soil contact underlining the fact that timely sowing

Table 4
Economic analysis of cropping cycles in 2021 and 2022 (mean value ± std. error (SE)). CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *Crotalaria juncea*, and CAM-maize under conservation agriculture with mixed cover crops (sunnhemp + cowpea + pearl millet).

Treatment	Year	Intermediate consumption – Before maize cycle (US$ ha^{-1})		Intermediate consumption (IC) – Maize cycle (US$ ha^{-1})						Gross product (GP) (US$ ha^{-1})	Gross value added (GVA) (US$ ha^{-1})	Labor (man-day ha^{-1})	Labor productivity (US$ man-day^{-1})
		Mungbean	Cover crops	Sowing	Fertilizer	Pest management	Weed management	Harvest & Transport	Total IC				
CT	2021	NA	49.7 (±3.6) c	112.1 (±0.4)	150.0 (±1.6)	15.6 (±2.4)	49.8 (±7.1)	195.9 (±21.9)	573.1 (±23.5)	1345.9 (±53.3)	772.8 (±43.7) a	20.8 (±1.0)	37.3 (±3.3)
CAS	2021	NA	124.2 (±3.4) b	87.6 (±10.6)	155.2 (±6.2)	19.9 (±3.4)	64.6 (±6.1)	169.8 (±38.0)	621.4 (±28.4)	1262.4 (±41.7)	641.0 (±18.1) b	19.8 (±0.4)	32.5 (±1.1)
CAM	2021	NA	141.0 (±3.4) a	87.6 (±10.6)	155.2 (±6.2)	19.9 (±3.4)	64.9 (±6.1)	150.7 (±31.0)	619.4 (±20.9)	1329.1 (±40.1)	709.8 (±37.3) ab	19.2 (±0.4)	37.1 (±2.1)
CT	2022	234.7 (±14.1)	135.7 (±17.8)	207.5 (±0.0) a	200.8 (±0.8)	36.7 (±8.1)	62.5 (±4.2)	145.8 (±7.9)	1023.7 (±1.6)	1565.4 (±124.1)	541.8 (±103.7) b	22.5 (±1.6)	25.6 (±5.5)
CAS	2022	201.5 (±16.4)	138.7 (±17.9)	172.5 (±0.0) b	200.8 (±0.8)	36.7 (±8.1)	62.5 (±4.2)	159.0 (±4.4)	971.7 (±0.5)	1787.8 (±14.8)	816.1 (±31.8) a	19.3 (±0.5)	36.8 (±1.3)
CAM	2022	201.6 (±16.3)	136.2 (±18.1)	172.5 (±0.0) b	200.8 (±0.8)	36.7 (±8.1)	62.5 (±4.2)	156.5 (±10.1)	966.8 (±0.4)	1700.3 (±89.1)	733.6 (±57.9) ab	21.7 (±0.4)	34.1 (±3.2)

* Different letters indicate difference among treatments at $p < 0.05$.
** Indicators without letters were non-significant difference at $p > 0.05$.

is critical in these Mollisols to achieve optimal soil moisture to reach an optimum seed-to-soil contact. Similarly, several studies emphasized that tillage systems (Blunk et al., 2021) type of press wheel and soil contact pressure (Braunack et al., 1988), soil moisture and soil aggregation (Brown et al., 1996) had significant effects on seed-soil contact, maize establishment and yield. Under warm, dry conditions and on fine-textured soils, poor emergence performance with shallow planting was observed, resulting in grain yield losses where seed-soil contact was less than optimal (Stewart et al., 2021). These authors reported that deep planting depths provided better emergence uniformity under these conditions. Under CT, the top soil was disrupted and disaggregated by successive passages of the plow which ensured better seed-to-soil contact than under both CA systems. By contrast, under CA systems, when sowing even in slightly damp soil, the sowing line is smoothed by the double passage of the discs (double disc for spreading fertilizer and double disc for sowing) resulting in poor seed-to-soil contact plus voids remaining around the seeds and the root systems in the early stage of the maize cycle. No-till sowing under CA systems was not optimal in either year and led to a reduction in plant density. Improved sowing management could help offset the reduction in the plant population. What is more, the first signs of an improvement of soil structure observed under CA may further help improve the seed-to-soil contact, thereby enabling more homogeneous emergence of the maize. However, despite the reduced number of plants, the yield of the plots under CA was not lower than under CT. This was detected after the CA systems had only been implement for 2–3 years and could be linked to compensation for the reduced plant density together with a potential positive impact of CA on crop performances. Kulagowski et al. (2021) found that CA consistently outperformed CT in yield, regardless of plant density. Similarly, Kutu (2012) reported that CA yielded more than CT under the same conditions. Haarhoff and Swanepoel (2018) noted that CA achieved greater yields with lower or comparable densities to CT.

On one hand, the economic data showed that intermediate consumption tended to be higher in CA systems than under CT with +8% ($p < 0.05$) and +2% (ns) in 2021 and 2022, respectively. This reinforces the need for CA systems to be more productive to offset the higher costs and to be as efficient as CT systems for farmers.

The early stages in the implementation of CA may result in lower agronomic performances compared to CT, but with a gradual improvement over time (Brouder and Gomez-Macpherson, 2014). A multicriteria analysis conducted by Xavier et al. (2020) showed that CA obtained better scores mainly for yield and labor criteria compared with CT. Although many authors have emphasized the benefits of CA, adoption by smallholder farmers could be slow and in some studies, even evaluations were even negative (Brown et al., 2017). To minimize the negative impact of the early stages of CA, some actions may be required to support adaptation and adoption by smallholder farmers including subsidies, specific extension support, access to new means of production, integration of a variety of crops into the system and extension policy to support CA (Brown et al., 2017; Ngwira et al., 2012). To minimize the negative impact in the early stage of the implementation, appropriate agronomic management must be carefully considered (Brouder and Gomez-Macpherson, 2014). In their assessment of early adoption of CA systems, Ngwira et al. (2013, 2012), showed that most of the systems and especially the maize-legume (*Cajanus cajan* L.) system not only benefitted soil health but also increased crop yield and produced positive economic returns compared to conventional cultivation of maize. These authors also mentioned that the total time and labor spent on crop production were less than using conventional methods. Although the cost of production was higher under CA, labor productivity was higher than under CT.

3.2. How do these systems evolve from one year to another?

Repeated measurements over two years made it possible to identify changers in the performances of the systems over time. We observed that,

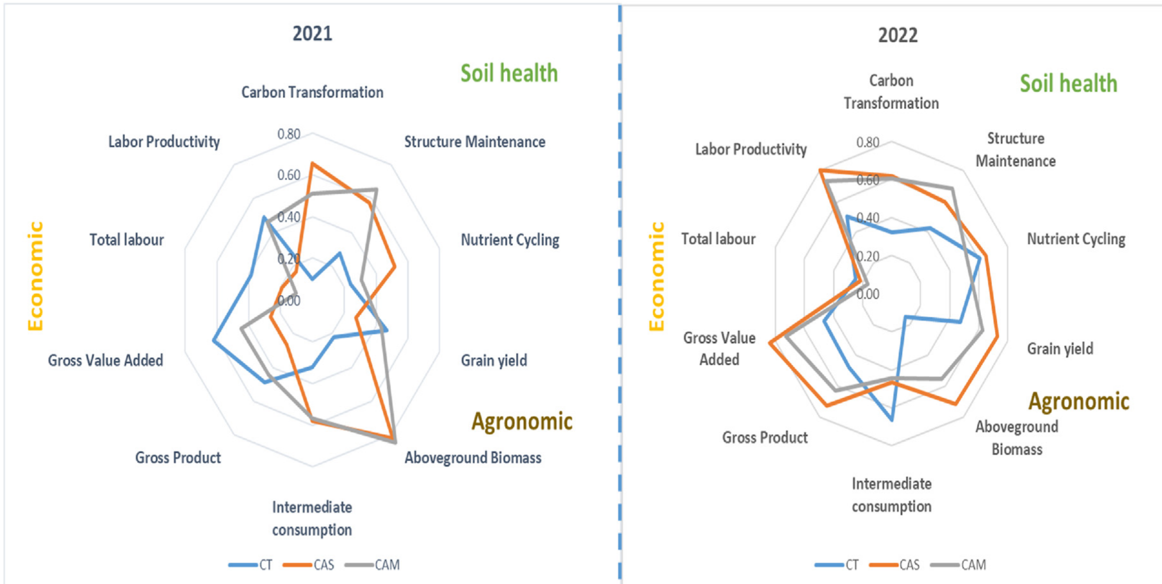

Fig. 3. Multi-criteria assessment of on-farm maize cropping systems in 2021 and 2022. CT-maize under conventional tillage with no cover crop and two ploughing operations, CAS-maize under conservation agriculture with *C. juncea* (sunnhemp), and CAM-maize under conservation agriculture with mixed cover crops (sunnhemp + cowpea + pearl millet).

out of ten soil parameters, five soil parameters (i.e., SituResp®, POXC, Cast, ExK, AggSurf) differed significantly between treatments in the two years, while two additional parameters (i.e., NH_4^+, AggSoil) only differed in 2021. It is often reported that amounts of above- and below-ground biomass produced and retained in the system are primarily responsible for the differential effects on soil C (West and Post, 2002; Sá et al., 2013). In our case, despite more than twice as much cumulative aboveground dry biomass under both CA systems (cumulative 2021–2022 of 20.2 t DM ha^{-1}) compared to under CT (cumulative 2021–2022 of 9 t DM ha^{-1}), the impact on labile-C pool was minimal (+10% under both CA systems) and was only significant over two years under CAS. By contrast, higher amplitudes were observed for SituResp® with an increase of +30% in 2021 and +111% in 2022. These results are in accordance with those obtained by Koun et al. (2023) who also observed a higher amplitude of change in SituResp® (+22%) compared with POXC (+5%) with the same treatments in 2020. While it is widely reported that increasing the amount of residues is essential to improve C transformation and increase soil C storage, interactions between plant residues and soil texture, soil microclimate (moisture and temperature) and pH ultimately determine rates of decomposition of plant residues and soil C turnover and storage. However, the alkalinity of these Mollisols could have a direct effect on the activity of extracellular enzymes synthesized by soil microbes and that play a central role in the biogeochemical cycling of nutrients. Turner (2010) emphasized that under high pH a range of enzymes (i.e., glucosidase, arylsulfatase) has reduced activity with an acidic optimum pH independent of soil pH. By contrast, other enzymes have an optimum activity that is consistent with soil pH. These reduced activities of a certain number of enzymes under this alkaline Mollisols may have a direct impact on carbon transformation and other soil parameters (nutrient availability), thereby slowing the potential improvement in SHI compared to other soil types (Pheap et al., 2019; Kulagowski et al., 2021). Besides the use of the current indicators that constitutes the SHI of Biofunctool®, additional soil microbial indicators should be integrated as they are more sensitive than labile-C, soil's chemical and physical properties to indicate early changes (Peixoto et al., 2010; Paz-Ferreiro and Fu, 2016). Several studies including those conducted by Mendes et al. (2019, 2021) emphasized the relevance of quantifying the activities of soil enzymes (β-glucosidase, cellulase, arylsulfatase and acid phosphatase) to characterize the SHI of tropical soils. It will be worth considering this kind of analysis in further researches in Cambodia to strengthen soil quality assessment and to elucidate through microbial indicators the rate of improvement in SHI between alkaline Mollisols and acidic Red Oxisols (Pheap et al., 2019).Although rarely significant, CAS showed a higher trend than CAM in three consecutive cropping seasons (2020–2022 Koun et al. (2023)) and higher POXC values than CAM. The cumulative effect of CA over continuous implementation for a longer period of time may lead to more resilient systems that are less sensitive to year-to-year changes. In the present study, agronomic and economic performances were still unstable at this stage of implementation with variability across the two cropping seasons, underlining the fact that, in this type of soil, intensification of the cropping system through the use of cover crops under no-till management did not yet produce a significant increase in productivity or in economic attributes. An implementation of such conservation agriculture systems over a longer period may help to exacerbate their effects on the performances of the system.

External parameters to the management practices also influenced these performances. Weather conditions have a key influence on soil and crops, and the difference in these conditions between 2021 and 2022 were significant. The differences in terms of rainfall distribution and especially the dry months following maize sowing in 2021 and water logging of the soil at the end of the maize cycle and just before soil measurements were taken in 2022 may have influenced the results of soil functioning and crop performances. The effects of management on soil functioning were more significant in 2021 under moist conditions after a long dry period than in 2022 after waterlogging preceding soil measurements. Concerning the crop, the contrary was observed with a significant effect of management practices on grain yield in 2022 whereas only a trend was observed in 2021. Concerning the economic indicators, key changes in prices were highlighted that were completely independent of the agronomic performances of the system. This variability hampers optimization of the economic performances of CA as prices and the farmers' income may affect the choice of management practices. Those two external factors (weather and prices) thus need to be fully integrated in the design of systems. A multicriteria monitoring tool should be made available to integrate these factors and enable farmers to adopt appropriate practices.

3.3. Is long-term adoption needed and possible?

We found that after three years CA systems are still in transition, and their performances is not yet be stable at this early stage. Despite initial trends especially with respect to soil health, the results of this study lead to rather variable conclusions. Longer and uninterrupted implementation of CA may be needed to achieve the results observed on soils in other long-term experiments in very contrasted contexts (Pheap et al., 2019; Kulagowski et al., 2021a). Longer studies were also reported to be needed to identify significant changes in yields under CA (Brouder and Gomez-Macpherson, 2014). A transition period was also observed in different compartments in the case of changes in practices, for example, in the conversion to organic vineyard systems (Merot and Smits, 2024).

In the case of annual cropping systems in conservation agriculture, repeated and long-term implementation of CA could be challenging in smallholders' farms (Pangapanga-Phiri et al., 2024). The performances of the systems are very sensitive to external factors (weather, prices) that are beyond the control of the farmers. Also, land use changes in the region are numerous and very rapid (Lienhard et al., 2020; Pravalprukskul et al., 2023), which make it complicated to design long-term systems without key support from technical institutions. This study was conducted in a context of very rapid transitions. Wealthier farmers (i.e. those with better financial assets and access to more agricultural land) had already changed land use to fruit tree plantations, mainly mango and longan (Kong et al., 2021), in an effort to diversify their sources of income and to cope with the price volatility of maize and cassava.

Our analysis did not include social indicators of the performance that would also be needed to undertake a complete multi-criteria analysis of the sustainability of the cropping systems. Prior to the study, we were unable to predict which indicators would be appropriate for this plot level analysis. However, for future studies, we recommend including the farmers' perception of the long-term stability of the implementation of CA. This would be critical for the long-term impact of CA practices and seems needed to reach the performance targets of the CA system.

4. Conclusion

The assessment of soil health in two consecutive cropping seasons showed that conservation agriculture with either single or using mixed species of cover crops contributed to better soil health compared with conventional tillage-based management (15% and 6% in 2021 and 2022 respectively). The higher soil health index under CA was primarily due to soil physical characteristics and to a lesser extent to carbon transformation, while nutrient function was less affected by the change in practices.

Agronomic analysis of the system in Mollisols revealed that early implementation of CA resulted in a lower plant population than CT. This difference in plant density between CT and CA was mainly due to the difference in seed to soil contact, emphasizing that, in Mollisols, the timeliness of sowing is critical to work when soil moisture is optimal. However, even with this difference in plant density, crop growth and yields were similar in both CA systems and CT. Appropriate-scale mechanisation to match prevailing soil conditions is an essential element that may currently be missing at the early stage of implementation. Moreover, under both CA systems, additional intermediate consumption due to the cost of cover crops could represent an additional obstacle for farmers at a stage when the positive impacts of the CA systems have not yet been achieved. This means that higher yields and increased profitability are preconditions for wide adaptation and adoption of CA by smallholder farmers. Our economic assessment revealed that implementation of both CA systems in the region could reduce labor requirements which is an advantage given the scarcity of labor in most of the farming systems in Cambodia.

The results of our combined analysis revealed that soil health was improved while agronomic and economic performances were still unstable at this early stage and in Mollisols. A longer-term assessment is needed to identify the transition pathways from conventional tillage-based to CA management but further innovations in agricultural practices and policies are also required to guarantee the future resilience of these Mollisols.

CRediT authorship contribution statement

Sambo Pheap: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexis Thoumazeau:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Jun Murase:** Writing – review & editing, Supervision, Conceptualization. **Vang Seng:** Writing – review & editing, Supervision. **Jean-Pierre Sarthou:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Veng Sar:** Writing – review & editing, Investigation. **Linda Kimbo:** Resources, Data curation. **Soklin Kheam:** Resources, Formal analysis, Data curation. **Pheakdey Chan:** Resources, Formal analysis, Data curation. **Pao Srean:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Samrith Leang:** Project administration, Investigation, Funding acquisition. **Lyda Hok:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Florent Tivet:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pheap Sambo reports financial support was provided by Cambodia Climate Change Alliance III. Pheap Sambo reports financial support was provided by Agroecology and Safe Food Systems Transition in Southeast Asia. Florent Tivet reports equipment, drugs, or supplies was provided by Bureau of Resilience, Environment, and Food Security. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.farsys.2025.100140.

References

Adeux, G., Guinet, M., Courson, E., Lecaulle, S., Munier-Jolain, N., Cordeau, S., 2022. Multicriteria assessment of conservation agriculture systems. Front. Agron. 4, 999960. https://doi.org/10.3389/fagro.2022.999960.

Bai, Z.G., Dent, D.L., Olsson, L., Schaepman, M.E., 2008. Proxy global assessment of land degradation. Soil Use Manag. 24, 223–234. https://doi.org/10.1111/j.1475-2743.2008.00169.x.

Basche, A.D., DeLonge, M.S., 2019. Comparing infiltration rates in soils managed with conventional and alternative farming methods: a meta-analysis. PLoS One 14, 1–22. https://doi.org/10.1371/journal.pone.0215702.

Black, C.A., 1965. In: Methods of Soil Analysis. Part II, second ed., 1985th ed. American Society of Agronomy Publishing No. 9, Madison.

Blouin, M., Hodson, M.E., Delgado, E.A., Baker, G., Brussaard, L., Butt, K.R., Dai, J., Dendooven, L., Peres, G., Tondoh, J.E., Cluzeau, D., Brun, J.-J., 2013. A review of earthworm impact on soil function and ecosystem services. Eur. J. Soil Sci. 64, 161–182. https://doi.org/10.1111/ejss.12025.

Blunk, S., Bussell, J., Sparkes, D., De Heer, M.I., Mooney, S.J., Sturrock, C.J., 2021. The effects of tillage on seed-soil contact and seedling establishment. Soil Till. Res. 206, 104757. https://doi.org/10.1016/j.still.2020.104757.

Bohoussou, Y.N.D., Kou, Y.H., Yu, W.B., Lin, B. jian, Virk, A.L., Zhao, X., Dang, Y.P., Zhang, H.L., 2022. Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: a global meta-analysis. Sci. Total Environ. 842, 156822. https://doi.org/10.1016/j.scitotenv.2022.156822.

Bongiorno, G., Bünemann, E.K., Oguejiofor, C.U., Meier, J., Gort, G., Comans, R., Mäder, P., Brussaard, L., de Goede, R., 2019. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecol. Indic. 99, 38–50. https://doi.org/10.1016/j.ecolind.2018.12.008.

Braunack, M.J., McDonald, W.K.J., Garside, A.L., 1988. Techniques for improving establishment of maize and soybean on cracking clay soils in the Burdekin River irrigation area. Qld. J. Agric. Anim. Sci. 45 (2), 97–103. http://era.dpi.qld.gov.au/id/eprint/13178/1/QJAAS_45[2]_1988_pp97-103_braunack.pdf.

Brouder, S.M., Gomez-Macpherson, H., 2014. The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. Agric. Ecosyst. Environ. 187, 11–32. https://doi.org/10.1016/j.agee.2013.08.010.

Brown, A.D., Dexter, A.R., Chamen, W.C.T., Spoor, G., 1996. Effect of soil macroporosity and aggregate size on seed-soil contact. Soil Till. Res. 38, 203–216. https://doi.org/10.1016/S0167-1987(96)01030-6.

Brown, B., Nuberg, I., Llewellyn, R., 2017. Negative evaluation of conservation agriculture: perspectives from African smallholder farmers. Int. J. Agric. Sustain. 15, 467–481. https://doi.org/10.1080/14735903.2017.1336051.

Cárceles Rodríguez, B., Durán-Zuazo, V.H., Soriano Rodríguez, M., García-Tejero, I.F., Gálvez Ruiz, B., Cuadros Tavira, S., 2022. Conservation agriculture as a sustainable system for soil health: a review. Soil Syst. 6, 87. https://doi.org/10.3390/soilsystems6040087.

Corsi, S., Muminjanov, H., 2019. Conservation Agriculture: Training Guide for Extension Agents and Farmers in Eastern Europe and Central Asia. Food and Agriculture Organization United Nations, Rome.

Craheix, D., Angevin, F., Doré, T., de Tourdonnet, S., 2016. Using a multicriteria assessment model to evaluate the sustainability of conservation agriculture at the cropping system level in France. Eur. J. Agron. 76, 75–86. https://doi.org/10.1016/j.eja.2016.02.002.

Dayet, A., Diepart, J.-C., Castella, J.-C., Sieng, S., Kong, R., Tivet, F., Demenois, J., 2024. Can organic rice certification curb the pressure of the agrarian transition in Cambodia? A farming system approach. Agric. Syst. 217, 103953. https://doi.org/10.1016/j.agsy.2024.103953.

Eze, S., Dougill, A.J., Banwart, S.A., Hermans, T.D.G., Ligowe, I.S., Thierfelder, C., 2020. Soil & Tillage Research Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. Soil Till. Res. 201, 104639. https://doi.org/10.1016/j.still.2020.104639.

FAO, 2021. Standard Operating Procedure for Soil Available Phosphorus - Olsen Method. Rome.

FEWS NET, 2023. Global Price Watch and Annex. https://fews.net/sites/default/files/2023-12/Global-PW-202311-Final.pdf. (Accessed 24 January 2025).

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res. 114, 23–34. https://doi.org/10.1016/j.fcr.2009.06.017.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use Manag. 27, 395–403. https://doi.org/10.1111/j.1475-2743.2011.00354.x.

Guppy, C., Martin, R., Wright, G., Flavel, R., Phan, S., Im, S., Tighe, M., 2017. Productivity and profitability of upland crop rotations in Northwest Cambodia. Field Crops Res. 203, 150–162. https://doi.org/10.1016/j.fcr.2016.12.010.

Haarhoff, S.J., Swanepoel, P.A., 2018. Plant population and maize grain yield: a global systematic review of rainfed trials. Crop Sci. 58, 1819–1829. https://doi.org/10.2135/cropsci2018.01.0003.

Herrick, J.E., Whitford, W.G., de Soyza, A.G., Van Zee, J.W., Havstad, K.M., Seybold, C.A., Walton, M., 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. Catena 44 (1), 27–35. https://doi.org/10.1016/S0341-8162(00)00173-9.

Hobbs, P.R., Sayre, K., Gupta, R., 2007. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363, 543–555. https://doi.org/10.1098/rstb.2007.2169.

Hok, L., de Moraes Sá, J.C., Boulakia, S., Reyes, M., Leng, V., Kong, R., Tivet, F.E., Briedis, C., Hartman, D., Ferreira, L.A., Magno, T., Pheav, S., 2015. Short-term conservation agriculture and biomass-C input impacts on soil C dynamics in a savanna ecosystem in Cambodia. Agric. Ecosyst. Environ. 214, 54–67. https://doi.org/10.1016/j.agee.2015.08.013.

IUSS Working Group WRB, 2022. In: World Reference Base for Soil Resources 2022: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, fourth ed. International Union of Soil Sciences, Vienna, Austria.

Jat, M.L., Chakraborty, D., Ladha, J.K., Rana, D.S., Gathala, M.K., McDonald, A., Gerard, B., 2020. Conservation agriculture for sustainable intensification in South Asia. Nat. Sustain. 3, 336–343. https://doi.org/10.1038/s41893-020-0500-2.

Jat, H.S., Choudhary, M., Kakraliya, S.K., Gora, M.K., Kakraliya, M., Kumar, V., Priyanka, Poonia, T., Mcdonald, A.J., Jat, M.L., Sharma, P.C., Abdallah, A.M., 2022. A decade of climate-smart agriculture in major agri-food systems: earthworm abundance and soil physico-biochemical properties. Agronomy 12, 658. https://doi.org/10.3390/agronomy12030658.

Knowler, D., Bradshaw, B., 2007. Farmers ' adoption of conservation agriculture : a review and synthesis of recent research. Food Policy 32, 25–48. https://doi.org/10.1016/j.foodpol.2006.01.003.

Kong, R., Diepart, J.C., Castella, J.C., Lestrelin, G., Tivet, F., Belmain, E., Bégué, A., 2019. Understanding the drivers of deforestation and agricultural transformations in the Northwestern uplands of Cambodia. Appl. Geogr. 102, 84–98. https://doi.org/10.1016/j.apgeog.2018.12.006.

Kong, R., Castella, J.-C., Suos, V., Leng, V., Pat, S., Diepart, J.-C., Sen, R., Tivet, F., 2021. Investigating farmers' decision-making in adoption of conservation agriculture in the Northwestern uplands of Cambodia. Land Use Policy 105, 105404. https://doi.org/10.1016/j.landusepol.2021.105404.

Koun, P., Vernet, P.-A., Filloux, T., Sar, V., Seng, V., Srimongkol, P., Tantachasatid, P., Sen, R., Pheap, S., Tivet, F., Thoumazeau, A., 2023. Early effects of conservation agriculture on soil organic carbon dynamics of Mollisols in Cambodia. Soil Use Manag. 40 (1), e12922. https://doi.org/10.1111/sum.12922.

Kulagowski, R., Thoumazeau, A., Leopold, A., Lienhard, P., Boulakia, S., Metay, A., Sturm, T., Tixier, P., Brauman, A., Fogliani, B., Tivet, F., 2021. Effects of conservation agriculture maize-based cropping systems on soil health and crop performance in New Caledonia. Soil Till. Res. 212, 105079. https://doi.org/10.1016/j.still.2021.105079.

Kutu, Fr, 2012. Effect of conservation agriculture management practices on maize productivity and selected soil quality indices under South Africa dryland conditions. Afr. J. Agric. Res. 7 (26), 3839–3846. https://doi.org/10.5897/AJAR11.1227.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an R package for multivariate analysis. J. Stat. Software 25, 1–18. https://doi.org/10.18637/jss.v025.i01.

Lienhard, P., Lestrelin, G., Phanthanivong, I., Kiewvongphachan, X., Leudphanane, B., Lairez, J., Quoc, H.T., Castella, J.-C., 2020. Opportunities and constraints for adoption of maize-legume mixed cropping systems in Laos. Int. J. Agric. Sustain. 18, 427–443. https://doi.org/10.1080/14735903.2020.1792680.

Liu, X., Lee Burras, C., Kravchenko, Y.S., Duran, A., Huffman, T., Morras, H., Studdert, G., Zhang, X., Cruse, R.M., Yuan, X., 2012. Overview of Mollisols in the world: Distribution, land use and management. Can. J. Soil Sci. 92 (3), 383–402. https://doi.org/10.4141/cjss2010-058.

Mafongoya, P., Rusinamhodzi, L., Siziba, S., Thierfelder, C., Mvumi, B.M., Nhau, B., Hove, L., Chivenge, P., 2016. Maize productivity and profitability in Conservation Agriculture systems across agro-ecological regions in Zimbabwe: a review of knowledge and practice. Agric. Ecosyst. Environ. 220, 211–225. https://doi.org/10.1016/j.agee.2016.01.017.

Masson, A.-S., Vermeire, M.-L., Leng, V., Simonin, M., Tivet, F., Nguyen Thi, H., Brunel, C., Suong, M., Kuok, F., Moulin, L., Bellafiore, S., 2022. Enrichment in biodiversity and maturation of the soil food web under conservation agriculture is associated with suppression of rice-parasitic nematodes. Agric. Ecosyst. Environ. 331, 107913. https://doi.org/10.1016/j.agee.2022.107913.

Mendes, I.C., Martinhão Gomes Sousa, D., Dario Dantas, O., Alves Castro Lopes, A., Bueno Reis Junior, F., Ines Oliveira, M., Montandon Chaer, G., 2021. Soil quality and grain yield: a win–win combination in clayey tropical oxisols. Geoderma 388, 114880. https://doi.org/10.1016/j.geoderma.2020.114880.

Mendes, I.C., Souza, L.M.D., Sousa, D.M.G.D., Lopes, A.A.D.C., Reis Junior, F.B.D., Lacerda, M.P.C., Malaquias, J.V., 2019. Critical limits for microbial indicators in tropical Oxisols at post-harvest: the FERTBIO soil sample concept. Appl. Soil Ecol. 139, 85–93. https://doi.org/10.1016/j.apsoil.2019.02.025.

Merot, A., Smits, N., 2024. Explaining yield dynamics during vineyard conversion to organic farming. Eur. J. Agron. 153, 127068. https://doi.org/10.1016/j.eja.2023.127068.

Ngwira, A.R., Aune, J.B., Mkwinda, S., 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. Field Crops Res. 132, 149–157. https://doi.org/10.1016/j.fcr.2011.12.014.

Ngwira, A.R., Thierfelder, C., Lambert, D.M., 2013. Conservation agriculture systems for Malawian smallholder farmers: long-term effects on crop productivity, profitability and soil quality. Renew. Agric. Food Syst. 28, 350–363. https://doi.org/10.1017/S1742170512000257.

Nicoloso, R.S., Rice, C.W., 2021. Intensification of No-till agricultural systems: an opportunity for carbon sequestration. Soil Sci. Soc. Am. J. 85 (5), 1395–1409. https://doi.org/10.1002/saj2.20260.

Nunes, M.R., Karlen, D.L., Veum, K.S., Moorman, T.B., Cambardella, C.A., 2020. Biological soil health indicators respond to tillage intensity: a US meta-analysis. Geoderma 369, 114335. https://doi.org/10.1016/j.geoderma.2020.114335.

Nut, N., Mihara, M., Jeong, J., Ngo, B., Sigua, G., Prasad, P.V.V., Reyes, M.R., 2021. Land use and land cover changes and its impact on soil erosion in stung sangkae catchment of Cambodia. Sustainability 13, 9276. https://doi.org/10.3390/su13169276.

Obriot, F., Stauffer, M., Goubard, Y., Cheviron, N., Peres, G., Eden, M., Revallier, A., Vieublé-Gonod, L., Houot, S., 2016. Multi-criteria indices to evaluate the effects of repeated organic amendment applications on soil and crop quality. Agric. Ecosyst. Environ. 232, 165–178. https://doi.org/10.1016/j.agee.2016.08.004.
Pangapanga-Phiri, I., Ngoma, H., Thierfelder, C., 2024. Understanding sustained adoption of conservation agriculture among smallholder farmers: insights from a sentinel site in Malawi. Renew. Agric. Food Syst. 39, e10. https://doi.org/10.1017/S1742170524000061.
Paz-Ferreiro, J., Fu, S., 2016. Biological indices for soil quality evaluation: perspectives and limitations. Land Degrad. Dev. 27, 14–25. https://doi.org/10.1002/ldr.2262.
Peixoto, R.S., Chaer, G.M., Franco, N., Reis Junior, F.B., Mendes, I.C., Rosado, A.S., 2010. A decade of land use contributes to changes in the chemistry, biochemistry and bacterial community structures of soils in the Cerrado. Antonie Leeuwenhoek 98, 403–413. https://doi.org/10.1007/s10482-010-9454-0.
Pheap, S., Lefèvre, C., Thoumazeau, A., Leng, V., Boulakia, S., Koy, R., Hok, L., Lienhard, P., Brauman, A., Tivet, F., 2019. Multi-functional assessment of soil health under Conservation Agriculture in Cambodia. Soil Till. Res. 194, 104349. https://doi.org/10.1016/j.still.2019.104349.
Pittelkow, C.M., Liang, X., Linquist, B.A., Van Groenigen, L.J., Lee, J., Lundy, M.E., Van Gestel, N., Six, J., Venterea, R.T., Van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368. https://doi.org/10.1038/nature13809.
Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174. https://doi.org/10.1016/j.agee.2016.01.005.
Prairie, A.M., King, A.E., Cotrufo, M.F., 2023. Restoring particulate and mineral-associated organic carbon through regenerative agriculture. Proc. Natl. Acad. Sci. USA 120, e2217481120. https://doi.org/10.1073/pnas.2217481120.
Pravalprukskul, P., Bruun, T.B., Messerli, P., 2023. Maize boom, bust and beyond: investigating land use transitions in the Northern Thai uplands. Land Use Policy 132, 106815. https://doi.org/10.1016/j.landusepol.2023.106815.
Rosa-Schleich, J., Loos, J., Mußhoff, O., Tscharntke, T., 2019. Ecological-economic trade-offs of diversified farming systems – a review. Ecol. Econ. 160, 251–263. https://doi.org/10.1016/j.ecolecon.2019.03.002.
Rusinamhodzi, L., Corbeels, M., van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron. Sustain. Dev. 31, 657–673. https://doi.org/10.1007/s13593-011-0040-2.
Sá, J.M.C., Bürkner Dos Santos, J., Lal, R., De Moraes, A., Tivet, F., Machado Sá, Briedis, C., De Oliveira Ferreira, A., Eurich, G., Farias, A., Friedrich, T., 2013. Soil-Specific Inventories of Landscape Carbon and Nitrogen Stocks under No-till and Native Vegetation to Estimate Carbon Offset in a Subtropical Ecosystem. Soil Sci. Soc. Am. J. 77 (6), 2094–2110. https://doi.org/10.2136/sssaj2013.01.0007.
Stagnari, F., Pagnani, G., Galieni, A., D'Egidio, S., Matteucci, F., Pisante, M., 2020. Effects of conservation agriculture practices on soil quality indicators: a case-study in a wheat-based cropping systems of Mediterranean areas. Soil Sci. Plant Nutr. 66, 624–635. https://doi.org/10.1080/00380768.2020.1779571.
Stewart, S., Kitchen, N., Yost, M., Conway, L.S., Carter, P., 2021. Planting depth and within-field soil variability impacts on corn stand establishment and yield. Agrosyst. Geosci. Environ. 4, e20186. https://doi.org/10.1002/agg2.20186.
Su, Y., Gabrielle, B., Makowski, D., 2021. The impact of climate change on the productivity of conservation agriculture. Nat. Clim. Change 11, 628–633. https://doi.org/10.1038/s41558-021-01075-w.
Thierfelder, C., Mhlanga, B., 2022. Short-term yield gains or long-term sustainability? – a synthesis of Conservation Agriculture long-term experiments in Southern Africa. Agric. Ecosyst. Environ. 326, 107812. https://doi.org/10.1016/j.agee.2021.107812.
Thierfelder, C., Matemba-Mutasa, R., Rusinamhodzi, L., 2015. Yield response of maize (Zea mays L.) to conservation agriculture cropping system in Southern Africa. Soil Till. Res. 146, 230–242. https://doi.org/10.1016/j.still.2014.10.015.
Thoumazeau, A., Gay, F., Alonso, P., Suvannang, N., Phongjinda, A., Panklang, P., Chevallier, T., Bessou, C., Brauman, A., 2017. SituResp®: a time- and cost-effective method to assess basal soil respiration in the field. Appl. Soil Ecol. 121, 223–230. https://doi.org/10.1016/j.apsoil.2017.10.006.
Thoumazeau, A., Bessou, C., Renevier, M.-S., Trap, J., Marichal, R., Mareschal, L., Decaëns, T., Bottinelli, N., Jaillard, B., Chevallier, T., Suvannang, N., Sajjaphan, K., Thaler, P., Gay, F., Brauman, A., 2019a. Biofunctool®: a new framework to assess the impact of land management on soil quality. Part A: concept and validation of the set of indicators. Ecol. Indic. 97, 100–110. https://doi.org/10.1016/j.ecolind.2018.09.023.
Thoumazeau, A., Bessou, C., Renevier, M.-S., Panklang, P., Puttaso, P., Peerawat, M., Heepngoen, P., Polwong, P., Koonklang, N., Sdoodee, S., Chantuma, P., Lawongsa, P., Nimkingrat, P., Thaler, P., Gay, F., Brauman, A., 2019b. Biofunctool®: a new framework to assess the impact of land management on soil quality. Part B: investigating the impact of land management of rubber plantations on soil quality with the Biofunctool® index. Ecol. Indic. 97, 429–437. https://doi.org/10.1016/j.ecolind.2018.10.028.
Turner, B.L., 2010. Variation in pH optima of hydrolytic enzyme activities in tropical rain forest soils. Appl. Environ. Microbiol. 76, 6485–6493. https://doi.org/10.1128/AEM.00560-10.
USDA, 2024. Grain and Feed. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileNamefileName=Grain and Feed Update_Bangkok_Thailand_TH2024-0071.pdf. Accessed 24 January 2025.
Van Pelt, R.S., Hushmurodov, S.X., Baumhardt, R.L., Chappell, A., Nearing, M.A., Polyakov, V.O., Strack, J.E., 2017. The reduction of partitioned wind and water erosion by conservation agriculture. Catena 148, 160–167. https://doi.org/10.1016/j.catena.2016.07.004.
von Törne, E., 1990. Assessing feeding activities of soil-living animals. I. Bait-lamina-tests. Pedobiologia 34, 89–101.
Wang, C., Zhang, G., Zhu, P., Chen, S., Wan, Y., 2023. Spatial variation of soil functions affected by land use type and slope position in agricultural small watershed. Catena 225, 107029. https://doi.org/10.1016/j.catena.2023.107029.
Weil, R.R., Islam, I.R., Stine, M.A., Gruver, J.B., Samson-liebig, S.E., 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. Am. J. Alternative Agric. 3–17.
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by Tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66 (6), 1930–1946. https://doi.org/10.2136/sssaj2002.1930.
White, P.F., Oberthür, T., Sovuthy, Pheav, 1997. The Soils Used for Rice Production in Cambodia: a Manual for Their Identification and Management. International Rice Research Institute, Manila, Philippines.
World Bank, 2023. Food Security Update. https://thedocs.worldbank.org/en/doc/40ebbf38f5a6b68bfc11e5273e1405d4-0090012022/related/Food-Security-Update-XCII-9-28-23.pdf. (Accessed 24 January 2025).
Xavier, J.H.V., Gomes, M.C., Anjos, F.S.D., Scopel, E., Silva, F.A.M.D., Corbeels, M., 2020. Participatory multicriteria assessment of maize cropping systems in the context of family farmers in the Brazilian Cerrado. Int. J. Agric. Sustain. 18, 410–426. https://doi.org/10.1080/14735903.2020.1788253.
Zhang, Y., Tan, C., Wang, R., Li, J., Wang, X., 2021. Conservation tillage rotation enhanced soil structure and soil nutrients in long-term dryland agriculture. Eur. J. Agron. 131, 126379. https://doi.org/10.1016/j.eja.2021.126379.