Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-025-10429-1

Regenerating productivity after soil fertility depletion in a 20-year cotton–maize rotation in Benin

Pierrot Lionel Yemadje · Isidore Amonmidé · Romain Loison · Michel Crétenet · Hermione Koussihouede · Awouminassi Marcellin Atakoun · Kenji Fujisaki · Santiago Dogliotti · Emmanuel Sekloka · Philippe Letourmy · Pablo Tittonell

Received: 10 March 2025 / Accepted: 29 July 2025

Abstract Soil degradation is a major challenge in Sub-Saharan Africa, where integrated soil fertility management has been promoted to restore productivity. A long-term experiment (1972–1992) run in Benin consisted of two phases: a depletion phase (1972–1980) with varying levels of mineral and organic fertilisation, and a regeneration phase (1981–1992) where all plots received full fertilisation and organic matter additions. Soils were sampled at 0–20 cm depth in 1973, 1974, 1982, and 1989 to assess fertility changes. Mineral fertilisation (N, P, K) and plant biomass management (crop residue retention and biomass additions) significantly influenced seed cotton and maize grain yields during the depletion phase. Soil organic carbon declined consistently in all treatments during depletion but remained stable during regeneration. The long-term effect was evident only in seed cotton yield during depletion. In contrast, due to high variability, maize grain yield showed no consistent trend. The combined use of organic resources and mineral fertilisers helped maintain crop productivity but led to declining soil chemical properties in this Ferralsol. The analysis of this outdated yet unpublished dataset shed light on how long-term soil depletion effects persist over time, even when soil fertility management is restored, indicating a

Michel Crétenet passed away during the study in 2022.

P. L. Yemadje (✉) · I. Amonmidé · R. Loison · E. Sekloka
Institute of Cotton Research (IRC), 01 PO Box 175, Cotonou, Benin
e-mail: pierrot-lionel.yemadje@cirad.fr

P. L. Yemadje · R. Loison
CIRAD, UPR AIDA, Cotonou, Benin

P. L. Yemadje · R. Loison · M. Crétenet · P. Letourmy · P. Tittonell
AIDA, Univ Montpellier, CIRAD, Montpellier, France

M. Crétenet · P. Letourmy · P. Tittonell
CIRAD, UPR AIDA, 34398 Montpellier, France

H. Koussihouede
UR Ecopédologie, Laboratoire de Sciences du sol, Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, BP 526 Cotonou, Benin

H. Koussihouede
CIRAD, UMR ABSys, 34398 Montpellier, France

A. M. Atakoun
Faculty of Agronomy (UP/FA), Integrated Production Systems Innovation Lab and Sustainable Land Management (InSPIREs-SLM), University of Parakou, Parakou, Benin

K. Fujisaki
INRAE, Info&Sols, 45075 Orléans, France

S. Dogliotti
Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay

P. Tittonell
Groningen Institute of Evolutionary Life Sciences, Groningen University, PO Box 11103, 9700 12 CC Groningen, The Netherlands

Published online: 20 August 2025

sort of 'soil memory'. The persistence of these effect suggests that regenerative interventions must begin before critical thresholds of degradation are crossed. Future research should focus on alternative measures to restore/maintain soil fertility not evaluated in this experiment, such as conservation tillage or legume integration, to provide long-term benefits for smallholder farmers facing soil fertility challenges.

Keywords Soil's memory · Crop residues · Long-term experiment · Cotton–maize yields · Soil organic carbon · Nutrient cycling

Introduction

In several countries of sub-Saharan Africa (SSA), crop yields declined due to nutrient limitations associated with soil degradation (Tully et al. 2015). This occurs when crop residue recycling and using mineral and organic fertilisers are insufficient to compensate for harvested nutrients and soil organic matter (SOM) losses (Vanlauwe et al. 2015). Mineral fertiliser is widely used globally to overcome nutrient deficiencies and increase crop yields (Martínez et al. 2017). It has been repeatedly claimed that soil organic matter and nutrient stocks can be built up by applying mineral fertilisers to crops and incorporating crop residue biomass into the soil (e.g., Huang et al. 2020; Tang et al. 2023). This hypothesis has been controversial in sub-Saharan Africa since its emergence (e.g., Khan et al. 2007; Tittonell and Giller 2013). However, the debate has been hampered by insufficient long-term evidence, particularly in tropical soils. Here, we analyse a 20-year experiment that was run before the paradigm of conservation agriculture arrived in Africa. It consisted of depleting soil fertility (from 1972 to 1980) and then regenerating it through mineral and organic soil amendments (from 1981 to 1992). Although outdated, this unpublished dataset offers a unique opportunity to assess the long-term impacts of alternative soil management practices and their regenerative potential in soils that are ploughed annually, as most smallholder farmers still do nowadays.

A recent meta-analysis that evaluated the contribution of mineral nitrogen (N) applications to building soil organic carbon (SOC) did not confirm the proclaimed positive effects of mineral fertilisers on SOC. It concluded that SOC quantities could only be increased by adding organic resources (OR) such as compost, manure, and crop residues (Gram et al. 2020), commonly used as primary nutrient sources to increase crop yields. Animal manure was the best performing OR (Mtangadura et al. 2017; Gram et al. 2020; Laub et al. 2023) as it allowed greater crop yields sustained over the long term, mineralized more nitrogen and phosphorus and better-regulated pH by providing nutrients such as Ca, Mg, and K. A long-term experiment in humid Central Kenya showed that maize yields increased with higher fertiliser input, but only up to a threshold, after which the increase in mineral fertiliser inputs did not significantly increase maize yields (Chivenge et al. 2009). In the same experiment, low-quality OR, such as sawdust and maize straw, even at C rates of 4 t ha^{-1}, did not increase yield compared to the control (without adding OR). In semiarid eastern Kenya, 5 t ha^{-1} of manure was needed to maintain yields and SOC in the long term (Micheni et al. 2004).

As animal manure is often scarce in smallholder farming systems in the tropics, particularly in SSA (Tittonell et al. 2010), crop residues are commonly used as organic resources to improve productivity and maintain soil fertility (Kintché et al. 2015; Yemadje et al. 2016; Mupangwa et al. 2020). Long-term studies show divergent effects of the combined use of inorganic fertiliser with OR on crop yields and SOC (Kintché et al. 2010; Detchinli and Sogbedji 2015; Koulibaly et al. 2015, 2017; Cardinael et al. 2022; Laub et al. 2023). The effects depend on the pedoclimatic conditions and prevailing agricultural management practices, such as the sequencing of crop rotations, the rate of mineral fertiliser application, and the organic matter quality and quantity. While some studies reported positive effects on grain productivity and agronomic efficiency of N (Gram et al. 2020), a meta-analysis of studies in SSA revealed that the combined use of organic resources (OR) and N fertilisers often results in negative interactive effects on yields (Chivenge et al. 2011).

Yet, in the absence of animal manure, the combined use of mineral fertiliser and crop residue incorporation has been touted as a sustainable practice that allows the replenishment of nutrients for better crop performance while having positive effects on soil biological (provision of substrate and nutrients for microbes- Zhong et al. 2010), chemical (buffering and pH changes and nutrient additions Kaur et al.

2005) and physical (stabilization of soil structure—Xin et al. 2016) properties. However, how lasting are these effects on soil quality? Is crop residue incorporation combined with mineral fertilisers enough to regenerate depleted soil productivity? To date, long-term studies investigating the effects of successive soil nutrient depletion and regeneration phases on SOC and crop performance in SSA are lacking. Few studies have focused on the long-term effect of combined mineral fertiliser and organic inputs on cotton–maize rotations in West Africa (e.g., Kintché et al. 2010; Ripoche et al. 2015). These studies, however, were characterized by small amounts of crop residues and high nutrient extraction rates associated with cotton cultivation, resulting in slow but continuous soil fertility depletion.

We analysed grey literature data from a long-term cotton–maize experiment with contrasting levels of N fertiliser and crop residues ploughed into the soil, run between 1972 and 1992 in Benin. The dataset had to be reconstructed from old handwritten field notes and machine-typed data reports. Our overall objective was to evaluate whether cotton–maize productivity, soil organic matter, and soil nutrients can be maintained in the long-term with mineral fertilisers alone or combined with crop residue biomass retention and extra plant biomass addition along a succession of soil nutrient depletion and regeneration phases in a Ferralsol, a common soil type used for agriculture in Benin.

Material and methods

Study site

The study area is part of the Benin administrative department of Couffo, which belongs to the Plateau zone (Azontondé et al. 2010). The long-term field experiment was conducted at the Aplahoue research station of the Benin National Research Institute (INRAB, Institut National des Recherches Agricoles du Benin), located in the agroecological zone I (i.e., the forest–savannah transition zone) of Benin (1° 40′ 25″ E, 6° 56′ 32″ N). The region has a subhumid Guinean climate (Aw, Köppen classification). The rainfall pattern is bimodal, suitable for a first crop cycle between April and July and a second cycle from September to November. The long rainy season alternates with the long dry season (December-March) and the short dry season (July–August), rarely exceeding two months. The second cropping season has been characterized by erratic rainfall events (Boko 1992). The mean annual rainfall was 1048 mm from 1972 to 1992. The mean air temperature was 27.7 °C. The mean minimum and maximum relative humidity were 52 and 95% respectively. Soils at the research station are defined as Ferralsol (Kidane et al. 2006), locally called "Terre de barre" (Kouelo et al. 2020). Soils of Aplahoue are known as deep (> 5 m) and highly permeable, leading to good physical and hydrological properties. The average soil properties of the field experiment indicate suitability for agricultural production, apart from a low organic matter and exchangeable K concentration (Table 1).

Long-term experiment

Experimental design

A continuous annual cotton–maize rotation experiment was established in 1972. No slopes or visible termite mounds, bumps, erosion bands, or colour differences were noticed in the experimental field. These fields have been cropped continuously with oil palm (*Elaeis guineensis Jacq*) in the previous years. The experiment was run until 1992 in two phases differing in soil management. The period from 1972 to 1980 was the "depletion phase," a combination of low and high rates of mineral fertilisers and crop residues that were applied as treatments in a randomized complete block design. During the depletion phase, there were

Table 1 Soil characteristics (horizon 0–20 cm) at the onset of the experiment in Aplahoue in 1972

Soil characteristics	Values
Clay (%)	11
Silt (%)	4
Sand (%)	85
OM (g kg^{-1})	11.4
Av. P (ppm)	21
Exchangeable Ca (g kg^{-1})	2.12
Exchangeable Mg (g kg^{-1})	2.1
Exchangeable K (g kg^{-1})	0.31
CEC ($cmol_{(+)}$ kg^{-1})	4.02
pH	6.2

two levels of mineral fertiliser application [yes/no] and aboveground (AGB) weed biomass management levels. The six treatments were applied on plots of 36 m^2 (6 m × 6 m) with eight replicates (48 plots):

F0a: no mineral fertiliser application and exportation of 100% of AGB crop residue biomass;

F0b: no mineral fertiliser application and maintenance of 100% of AGB crop residue biomass;

F0c: no mineral fertiliser application, maintenance of 100% of AGB crop residue biomass, and incorporation (ploughing into the soil) of 10 t ha^{-1} $year^{-1}$ of weed biomass;

F1a: F0a + application of mineral fertiliser (MF: 125 N + 92 P + 56 K kg ha^{-1} yr^{-1});

F1b: F0b + application of MF; and.

F1c: F0c + application of MF.

For the treatments, F0c and F1c, the weed biomass was a mix of *Imperata cylindrica* and *Cynodon dactylon* straw collected from a neighbouring field.

The period from 1981 to 1992 is called the "regeneration phase". The F1c treatment (mineral fertiliser + crop residue + weed biomass) was applied to all the experimental plots during this period to analyse the legacy effects of the depletion phase. All plots were tilled during the experiment duration. In 1981, no yield data were recorded. However, starting that year, all plots began receiving the F1c treatment (i.e., mineral fertiliser + crop residue retention + 10 t ha^{-1} $year^{-1}$ of weed biomass incorporation). This marked the beginning of the regeneration period, designed to evaluate the legacy effects of prior soil nutrient depletion under a uniform rehabilitation regime.

Crop management

Each year, maize was cropped during the first season, followed by cotton during the second season (Table 2). The soil was ploughed once a year at the start of each cropping season before maize was sown. The local maize variety NOVARA (90-day crop cycle) was used for the experiment. Maize was sown mid-March with three or four seeds per hole and then thinned at two plants per hole two weeks after sowing, leading to a density of 62,500 plants per hectare (0.8 m × 0.4 m spacing). 4 l ha^{-1} of PRIMEXTRA (Atrazine) was applied from 1972 to 1983, and 4 l ha^{-1} of PRIMAGRAM

Table 2 A summary of crop management variables for both cotton and maize

Practice	Cotton	Maize
Seed varieties	IRMA 96 + 97 (180-day cycle)	NOVARA (90-day cycle)
Spacing (cm)	0.80 m × 0.30 m	0.80 m × 0.40 m
Expected population per ha	41,666	62,500 (two plants per spot)
Basal mineral fertiliser	200 kg ha^{-1} of $N_{14}P_{23}K_{14}$	200 kg ha^{-1} of $N_{14}P_{23}K_{14}$
Topdressing fertiliser	100 kg ha^{-1} of urea (46%N)	50 kg ha^{-1} of urea (46%N)
Weed management	*Clearing before planting:*	*Clearing before sowing*
Pest control	Glyphosate (2 l ha^{-1}) *Pre-emergent control:* 4 l ha^{-1} of COTODON® G 560 SC herbicide (250 g l^{-1} of Fluometuron, 250 g l^{-1} of Prometryn, and 60 g l^{-1} of Glyphosate) Post-emergent control: Two manuals weeding at 20 and 90 Days After Planting	Glyphosate (2 l ha^{-1}) *Pre-emergent control:* 4 l ha^{-1} of PRIMEXTRA (Atrazine) from 1972 to 1983 and 4 l ha^{-1} of PRIMAGRAM (S-Metolachlor and Atrazine) from 1984 to 1992 *Post-emergent control:* Two manuals weeding at 20 and 45 Days After Sowing
	Phyllophagous Insects: 500 ml ha^{-1} of Thalis 56/112 EC (24 g l^{-1} Emamectin benzoate, and 32 g l^{-1} Acetamiprid) *Mites control* 500 ml ha^{-1} of PYRO FTE 672 EC (72 g l^{-1} Cypermethrin, and 600 g l^{-1} Chlorpyrifos-ethyl) *Carp pests control*: 100 ml/ha of Belt (Flubendiamide 240 g l^{-1}, and Thiacloprid 240 g l^{-1})	500 ml ha^{-1} of Thalis 56 / 112 EC (24 g l^{-1} Emamectin benzoate, and 32 g l^{-1} Acetamiprid) for fall armyworm control

(S-Metolachlor and Atrazine) from 1984. These herbicides were applied on the day of sowing of the maize. Two mechanical weeding operations (with a hoe) were done 20 and 45 days after sowing (DAS) of the maize. A fertiliser dose of 200 kg ha^{-1} of NPK (14-23-14) (corresponding to 28 kg N ha^{-1}, 46 kg P ha^{-1}, 28 kg K ha^{-1}) and 50 kg ha^{-1} of urea (corresponding to 23 kg N ha^{-1}) were spot-applied near the neck of the maize plants at 20 and 45 DAS, respectively. The maize cobs were harvested each year at the end of June.

Cotton was planted when the maize crop matured, which led to about two weeks of their cohabitation. The recommended 180-day crop cycle, cotton variety IRMA 96 + 97 was planted mid-June of each year at a density of 41,666 plants per ha (0.8 m × 0.3 m spacing) with two seeds per hole and then thinned to one plant per hole. A fertiliser dose of 200 kg of NPKSB (14-23-14) (corresponding to 28 kg N ha^{-1}, 46 kg P ha^{-1}, 28 kg K ha^{-1}), and 100 kg urea (corresponding to 46 kg N ha^{-1}) was applied to all plots at 15 and 40 days after planting (DAP), respectively. Fertilisers were banded in a closed row near the plants. Application of 4 l ha^{-1} of COTODON® G 560 SC herbicide (250 g l^{-1} of Fluometuron, 250 g l^{-1} of Prometryn, and 60 g l^{-1} of Glyphosate) was carried out on the day of cotton planting. In addition, two mechanical weeding operations (with a hoe) were performed at 20 and 90 days after planting (DAP) of cotton. The cotton harvesting (seed + lint) was done at the end of December each year after the cotton bolls had been fully opened at 170 DAP. After each harvest, maize stalks and cotton plants were cut and left in the inter-rows only for some treatments (F0b, F0c, F1b, F1c).

Measured variables

Maize and cotton yields

Harvested maize grain and seed cotton were weighed, and annual average yields per treatment were calculated.

Soil sampling and analysis

Soils were sampled at 0–20 cm depth four times during the long-term experiment in 1973, 1974, 1982, and 1989. Soil samples were taken in February/March before establishing the first crop each year. Five soil samples were taken along the diagonals of each elementary plot using an auger and then mixed to obtain one composite sample per treatment per repetition. Each sample was analyzed for pH (soil/water ratio of 1:2.5), total organic C (Walkley and Black 1934) and total N, available P (Olsen), exchangeable K, Ca, and Mg (extraction in 1N ammonium acetate). Soil samples were analyzed in the Cirad laboratory in Montpellier (France).

Calculated variables

Nutrient (NPK) factor productivity and agronomic use efficiency by treatment and phase

Factor productivity (FP), referring to the efficiency with which plants convert applied nutrients (like nitrogen, phosphorus, and potassium) into yield or biomass, has been determined according to Eq. 1.

$$FP_{\{N,P,K\}} = \frac{Y_{F1\{N,P,K\}}}{N,P,K_{(applied)}} \tag{1}$$

where $FP_{\{N,P,K\}}$ refers to factor productivity for N, P, or K. Y_{F1} refers to maize grain or seed cotton yields (kg ha^{-1}) in mineral (N, P, K) fertiliser treatments. $N,P,K_{(applied)}$ is the amount of mineral (N, P, K) fertiliser applied (kgN ha^{-1}, kgP ha^{-1}, kgK ha^{-1}).

The agronomic N use efficiency (N_AE, kg N^{-1}) was defined as the increase in maize grain or seed cotton yield per unit of mineral N fertiliser applied (Vanlauwe et al. 2011) according to Eq. 2.

$$N\_ANAE_{\{a,b,c\}} = \frac{Y_{F1\{a,b,c\}} - Y_{F0\{a,b,c\}}}{N_{applied}} \tag{2}$$

where Y_{F1} refers to maize grain or seed cotton yields (kg ha^{-1}) in the treatment where N has been applied. Y_{F0a} refers to maize grain or seed cotton yields (kg ha^{-1}) in the control treatments without mineral N fertiliser and 100% crop residue export, either Y_{F0b} for treatments with crop residue maintenance or Y_{F0c}

for treatments with incorporation and the addition of 10 t ha^{-1} of weeds biomass ploughed into the soil. $N_{applied}$ is the amount of mineral N fertiliser applied (kgN ha^{-1}). The same equation was used to determine agronomic P and K use efficiency.

Estimated average yield per sub-phase

Four sub-phases were considered according to the initial and final sub-period of each phase (initial depletion (1972 to 1975), final depletion (from 1976 to 1980), initial regeneration (from 1982 to 1987), and final regeneration (from 1988 to 1992)) to estimate the average seed cotton and maize yield per sub-phase.

Data analysis

Mixed models with interactions were used on seed cotton and maize yield data, with Treatment and Year as fixed factors, follow by pairwise comparison independently in the depletion and regeneration phases. In the mixed-effects model, Block was included as a random effect, while Treatment, Year, and their interaction were considered fixed effects. This allowed us to account for spatial variability and repeated measurements across the experimental layout. The mixed model was used for nutrient factor productivity, agronomic use efficiency, soil fertility data, and covariance analyses on cotton and maize yields, with treatment, phase, and year as fixed factors. To analyse treatment effects, we decomposed the full treatment structure into two crossed factors: (1) crop residue management (with/without) and (2) mineral fertiliser application (with/without), to evaluate interaction effects. Temporal analysis was conducted separately within each phase (depletion and regeneration) to avoid statistical collinearity between 'year' and 'phase.' Mixed-effects models included 'year' as a fixed effect when assessing trends within each phase, and 'block' as a random effect. Analyses of variance (ANOVA) and covariance (ANCOVA) were conducted using R, with separate models run for the depletion and regeneration phases to avoid confounding due to the temporal definition of phases. Within each phase, the sub-periods (initial vs. final) were used for descriptive comparison. Tukey's HSD test (5% level) was applied for pairwise comparison of treatment means when significant effects were detected.

Results

Seed cotton and maize grain yield

Changes in cotton and maize yields during the depletion phase from 1972 to 1980 and the regeneration phase from 1981 to 1992 are shown in Fig. 1. During the depletion and regeneration phases, treatment effects were consistently significant ($p < 0.05$) on both cotton and maize yields.

Depletion phase

Seed cotton yields were virtually nil, and maize yields decreased rapidly under the control treatments F0a (no fertiliser, no crop residue incorporation) during the depletion phase (Fig. 1). Crop residue incorporation without fertiliser use (F0b) induced small improvement in seed cotton yields. However, it led to average maize yields similar to those attained by farmers in the region (1470 kg ha^{-1}) in the previous years. When mineral fertilisers were added without crop residue incorporation (F1a), cotton yields were still low (377 ± 144 kg ha^{-1}) and declining. At the same time, maize yields were higher than the regional average (2026 kg ha^{-1}) but declined too over time (from 1397 kg ha^{-1} in 1972 to 686 kg ha^{-1} in 1980) see Table 3. When fertiliser use was combined with crop residue incorporation (F1b), cotton yields gradually increased, but their average (985 kg ha^{-1}) fluctuated around the regional yields farmers obtained. In contrast, maize yields were similar to those receiving only mineral fertilisers (F1a), and declined over time. Cotton and maize yields were increased and maintained only in treatments that incorporated crop residues and added weed biomass (F0c and F1c), irrespective of fertiliser use in the case of cotton, and producing barely 300 kg ha^{-1} extra yield with fertilisers in the case of maize.

Regeneration phase

Average seed cotton yields during the initial sub-period (1982–1987) of the regeneration phase were 2330 ± 675.7 kg ha^{-1} and 2253 ± 754.9 kg ha^{-1} in

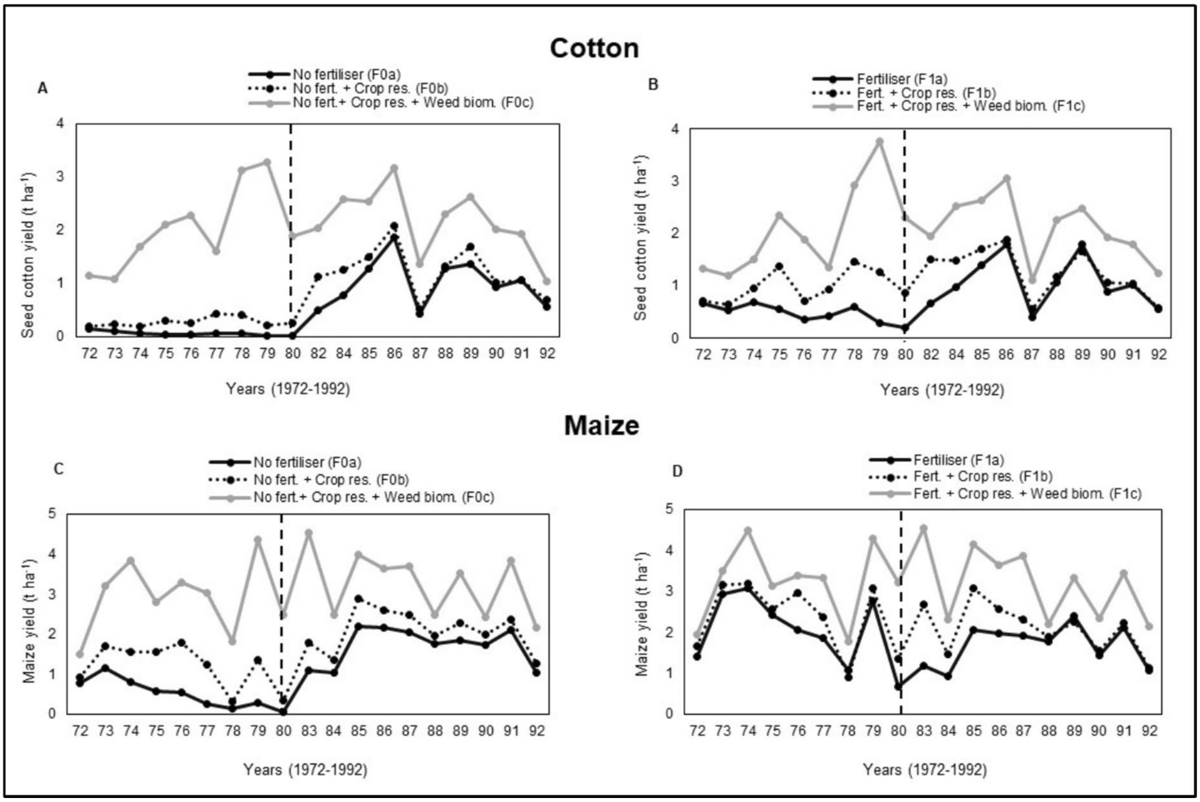

Fig. 1 Seed cotton (upper) and maize (lower) yield in Aplahoue from 1972 to 1992. F0a without mineral fertiliser (MF) and crop residues removing, F0b: without MF and restitution of crop residues, F0c: without MF and restitution of crop residues with inputs of 10 t ha^{-1} year^{-1} F1a: F0a with MF, F1b: F0b with MF, F1c: F0c with MF. Vertical dotted lines in 1980 indicate the end of the depletion phases

fields subject to F0c and F1c treatments in the previous phase, respectively. The corresponding average maize yields were (F0c) 3666 ± 753 kg ha^{-1} and (F1c) 3705 ± 841.6 kg ha^{-1}. All other treatments during the regeneration phase failed to achieve the yields obtained with the initial F1c and F0c treatments for both cotton and maize (Fig. 1). The treatments that combined fertiliser use with crop residue incorporation from 1972 to 1980 produced yields similar to the final years of the regeneration phase (20 years later) compared to treatments in which no fertilisers were used and no crop residues were incorporated. Such a negative legacy effect was not overcome by adding fertiliser, crop residues, and weed biomass to the soil during the regeneration phase.

Effect of mineral fertiliser use

Mineral fertilisation did not affect yields when crop residues were incorporated, and 10 t ha^{-1} year^{-1} of weeds biomass ploughed into the soil (cf. F0c vs. F1c) during the depletion and regeneration phases. Cotton yields initially increased with fertiliser use compared to non-fertilized controls but only significantly when crop residues were incorporated (Fig. 1; Table 3). Fertiliser use without crop residue retention led to a decline in cotton yield during the depletion phase. Maize responded to fertiliser use during the depletion phase in treatments without crop residue retention but tended to decline over time. Generally, the seed cotton and grain maize yield increased from the initial to the final

Table 3 Average yields of cotton and maize yields at the beginning and the end of the depletion and regeneration phases of the experiment

Treatment	Depletion phase		Regeneration phase	
	Initial (1972–1975)	Final (1976–1980)	Initial (1982–1987)	Final (1988–1992)
Average seed cotton yield ± std (kg ha^{-1})				
No fertiliser (F0a)	85 ± 43 Bc	41.6 ± 22 Bc	972.4 ± 602 Ac	1034 ± 319 Ab
No fert. + Crop res. (F0b)	229 ± 53 Bc	309 ± 93 Bb	1289 ± 568 Ab	1157 ± 375 Ab
No fert. + Crop res. + Weed biom. (F0c)	1507 ± 49 Ba	2429 ± 737 Aa	2330 ± 675 Aa	1982 ± 588 Aa
Fertiliser (F1a)	610 ± 78 Bbc	377 ± 144 Cb	1049 ± 559 Ac	1064 ± 450 Ab
Fert. + Crop res. (F1b)	915 ± 33 Bb	1042 ± 310 Aab	1426 ± 518 Ab	1109 ± 390 Ab
Fert. + Crop res. + Weed biom. (F1c)	1596 ± 52 Ba	2447 ± 939 Aa	2253 ± 754 Aa	1943 ± 477 Aa
SED	236.2	211.3	211.3	211.3
p value	< 0.001	< 0.001	0.017	0.03
Average maize yield ± std (kg ha^{-1})				
No fertiliser (F0a)	827 ± 242 Bd	251 ± 186 Bc	1710 ± 587 Ac	1696 ± 392 Ac
No fert. + Crop res. (F0b)	1430 ± 351 Bcd	1014 ± 662 Bbc	2216 ± 630 Ab	1976 ± 433 Ab
No fert. + Crop res. + Weed biom. (F0c)	2844 ± 988 Aab	2996 ± 955 Aa	3666 ± 753 Aa	2886 ± 749 Aa
Fertiliser (F1a)	2456 ± 760 Ab	1682 ± 822 Ab	1614 ± 518 Ac	1760 ± 527 Ac
Fert. + Crop res. (F1b)	2647 ± 709 Ab	2131 ± 976 Aab	2420 ± 600.8 Ab	1809 ± 476 Ab
Fert. + Crop res. + Weed biom. (F1c)	3266 ± 1053 Aa	3198 ± 902 Aa	3705 ± 841 Aa	2697 ± 640 Aa
SED	336.4	300.9	300.9	300.9
p value	< 0.001	0.015	0.043	0.026

F0a without mineral fertiliser (MF) and crop residues removing, F0b: without MF and restitution of crop residues, F0c: without MF and restitution of crop residues with inputs of 10 t ha^{-1} year^{-1} F1a: F0a with MF, F1b: F0b with MF, F1c: F0c with MF. Low case letters indicate statistically different treatment means at $p < 0.05$ in a Tukey test. Same capital letter upon the same treatment at different sub-periods indicate that there is no significant of that treatment over phase or sub-period sub-period of the depletion phase, while it tended to be constant during the entire regeneration phase.

Nutrient (N, P, K) factor productivity

The N, P, and K factor productivities of seed cotton yield calculated for mineral fertiliser use were significantly affected by the treatments only during the initial sub-period (1972–1975) of the depletion phase and during the final sub-period (1988–1992) of the regeneration phase (Fig. 2, $p < 0.05$), while no significant effects were observed for maize. The N factor productivity (NFP) of cotton also showed significant ($p < 0.05$) differences between treatments during the final sub-period of the depletion phase (1976–1980). The highest factor productivity was recorded for each nutrient (N, P, K) with F1c treatment at both phases. Applying mineral fertiliser, incorporating crop residue biomass, and adding 10 t ha^{-1} $year^{-1}$ of weed biomass induced cotton to produce a relatively large yield per unit of nutrient applied. The general long-term effect indicated a significant increase in nutrient factor productivity during the depletion phase, while stability was observed during the regeneration phase.

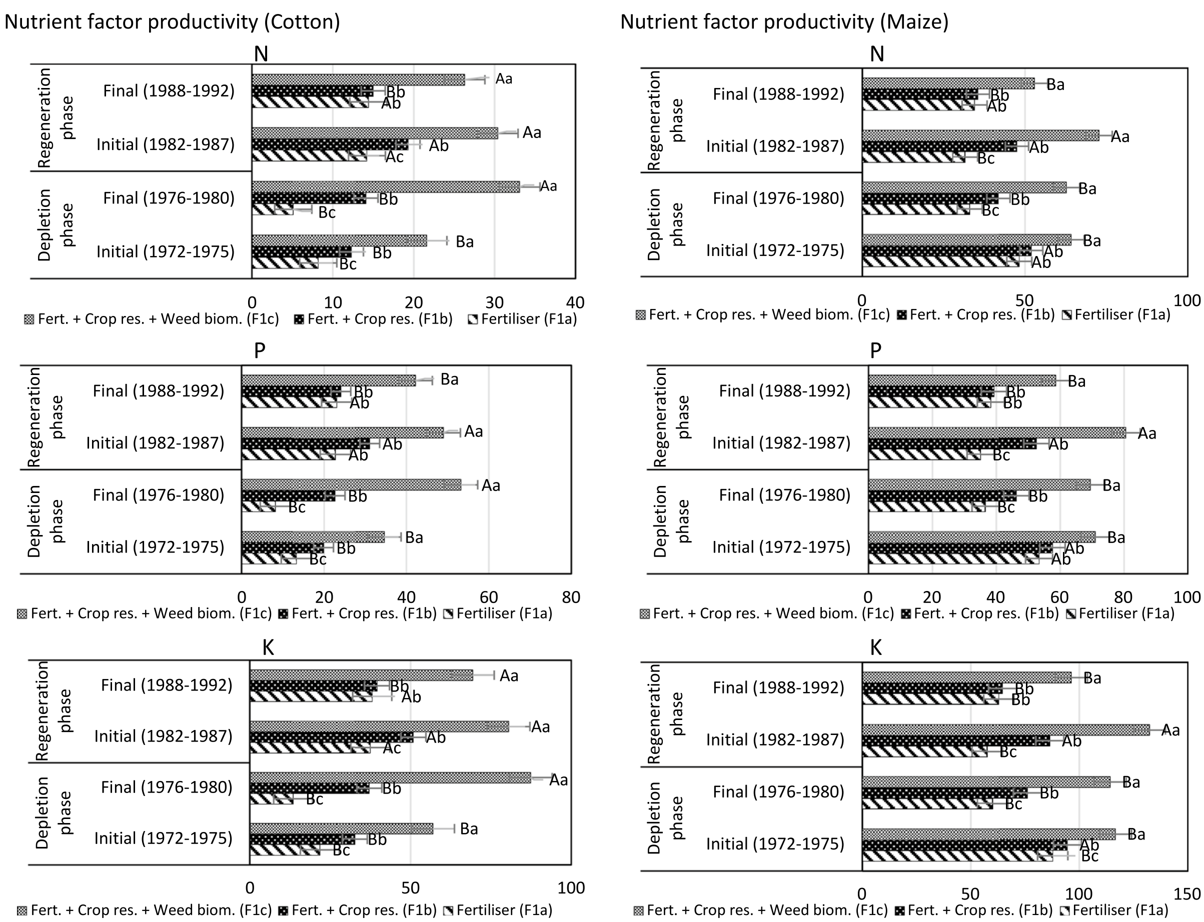

Fig. 2 Nutrient (NPK) factor productivity by treatment and phase. F0a without mineral fertiliser (MF) and crop residues removing, F0b: without MF and restitution of crop residues, F0c: without MF and restitution of crop residues with inputs of 10 t ha^{-1} $year^{-1}$ F1a: F0a with MF, F1b: F0b with MF, F1c: F0c with MF. The letters stand for Tukey's mean separation test. The same capital letter upon the same treatment at different sub-periods indicates no significance of that treatment over a phase or sub-period. The same lower character upon two different treatments at the same sub-period indicates no significant effect between these treatments at that sub-period or phase

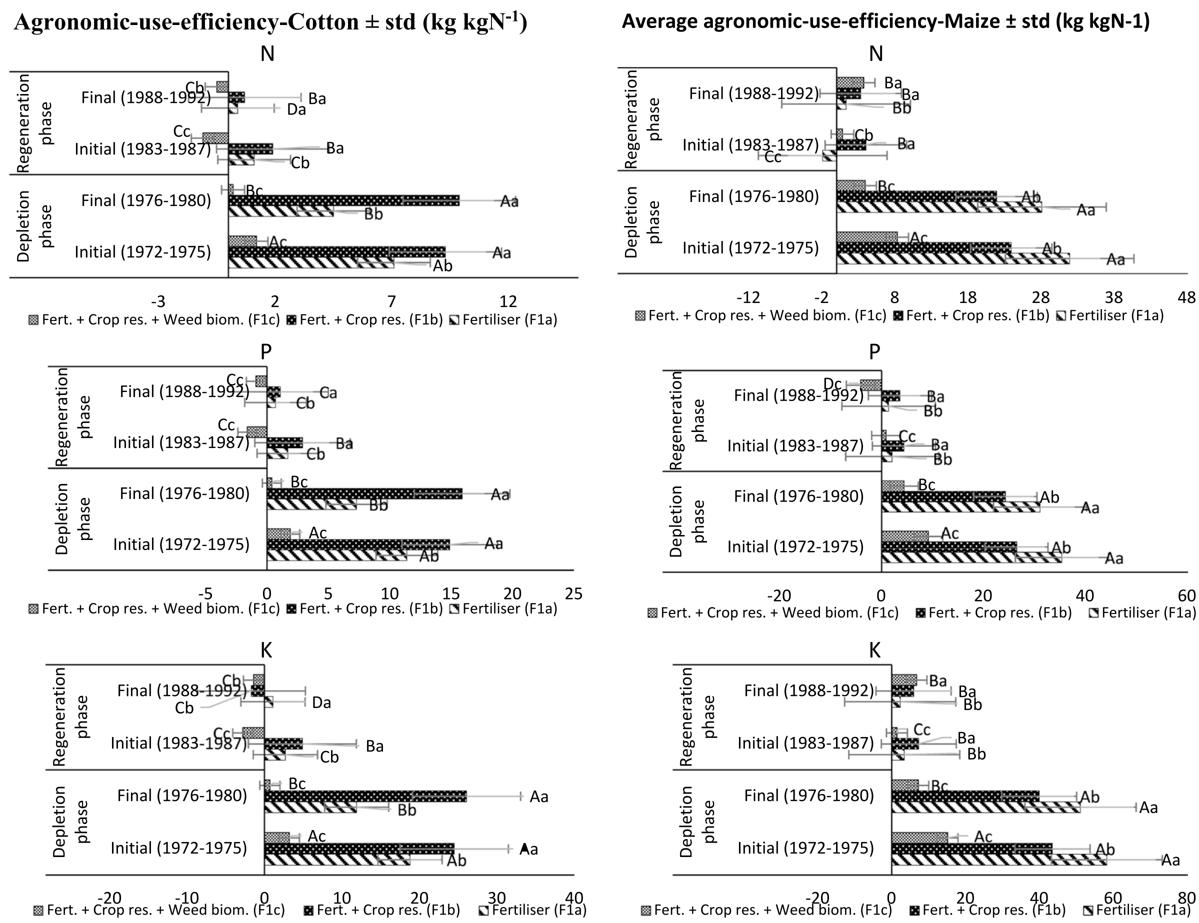

Fig. 3 Agronomic use efficiency of N, P, and K by treatment and phase. F0a without mineral fertiliser (MF) and crop residues removing, F0b: without MF and restitution of crop residues, F0c: without MF and restitution of crop residues with inputs of 10 t ha^{-1} year^{-1} F1a: F0a with MF, F1b: F0b with MF, F1c: F0c with MF. The letters stand for Tukey's mean separation test. The same capital letter upon the same treatment at different sub-periods indicates that there is no significance of that treatment over a phase or sub-period. The same lower character upon two different treatments at the same sub-period indicates no significant effect between these treatments at that sub-period or phase

Agronomic N, P, and K use efficiency

During the depletion phase, the different treatments significantly affected the agronomic use efficiency (AE) of N, P, and K fertiliser by cotton and maize (Fig. 3). Incorporating crop residues and adding 10 t ha^{-1} year^{-1} of weed biomass ploughed into the soil significantly reduced both crops' response to mineral fertiliser additions. In other terms, when keeping crop residues and adding extra biomass, mineral fertiliser application became redundant, as was already shown by the average yields (cf. Table 3), leading to negative nutrient use efficiencies during the regeneration phase. In the final sub-period (1976–1980) of the depletion phase, the values of 0.2 ± 1.5 kg kg N^{-1}, 0.4 ± 1.8 kg kg P^{-1}, and 0.7 ± 1.5 kg kg K^{-1} were observed for cotton, while 3.9 ± 2.5 kg kgN^{-1}, 4.4 ± 2.3 kg kg P^{-1}, and 7.2 ± 1.9 kg kg K^{-1} were observed for maize. During the regeneration phase, the treatment F1c negatively affected N, P, and K agronomic use efficiency (respectively, -1.1 ± 1.3 kg kgN^{-1}, -1.6 ± 1.7 kg kg P^{-1}, and -2.8 ± 1.4 kg kg K^{-1} for initial sub-period, and respectively -0.5 ± 0.9 kg kg N^{-1}, -0.9 ± 1.2 kg kg P^{-1}, -1.4 ± 1.9 kg kg K^{-1}) for cotton. The long-term effect indicated a general stability of agronomic use

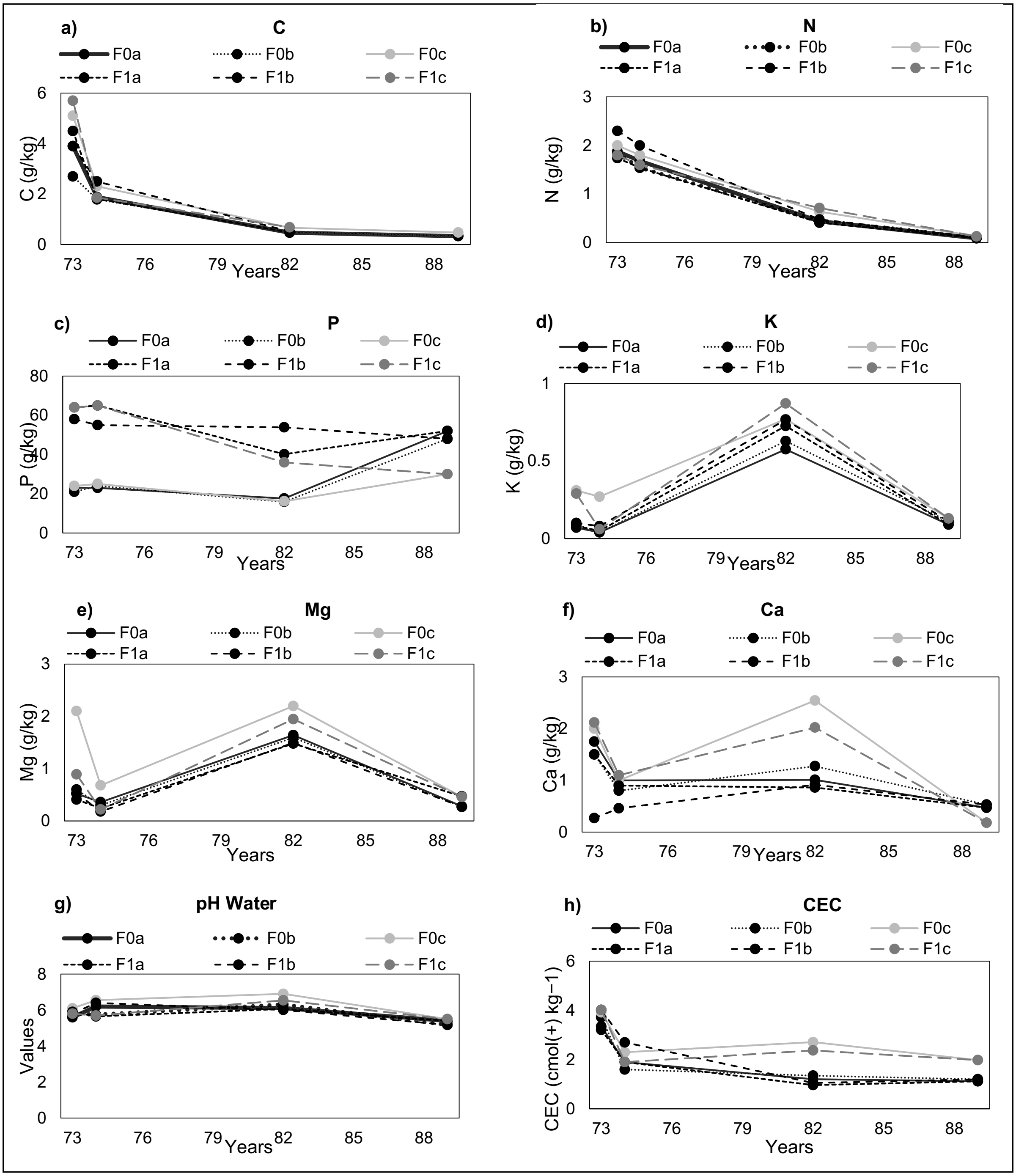

Fig. 4 Soil chemical properties evolution from 1973 to 1989. CEC: cation exchange capacity, K: potassium, Ma: magnesium, C: carbon, P: phosphorus, Ca: calcium, N: nitrogen, F0a without mineral fertiliser (MF) and crop residues removing, F0b: without MF and restitution of crop residues, F0c: without MF and restitution of crop residues with inputs of 10 t ha^{-1} $year^{-1}$ F1a: F0a with MF, F1b: F0b with MF, F1c: F0c with MF

efficiency during the depletion phase across all treatments while significant decreases were observed during the regeneration phase.

Changes in soil fertility

Soil properties significantly varied over the years and treatments (Fig. 4). Despite the differences in productivity created by the different treatments over time, the soil organic carbon and total nitrogen contents decreased consistently for all treatments during the depletion phase (from 5.7 to 1.8 g/kg and from 1.6 to 0.71 g/kg, respectively) and remained almost constant during the regeneration phase (from 0.6 to 0.3 g/kg, and from 0.71 to 0.13 g/kg respectively) (Fig. 4). However, soil potassium, magnesium, and calcium content showed particularly an increase from the initial to the final sub-period of the depletion phase (from 0.29 to 0.87 g/kg, 0.89 to 1.94 g/kg, and 2.12 to 2.4 g/kg, respectively), before declining during the regeneration phase (0.87 to 0.13 g/kg, 1.94 to 0.46 g/kg, and from 2.02 to 0.18 g/kg respectively). No significant differences in treatments were observed for phosphorus, pH, and CEC over the years. The large variability in soil organic carbon values in 1973 likely reflects heterogeneity in residue decomposition and soil conditions following the transition from oil palm cover.

Discussion

This study aimed to assess the long-term effect of organic resources and mineral fertiliser application on cotton–maize productivity and soil chemical properties. The results revealed that using organic resources could maintain crop productivity over the long term, even without mineral fertiliser application. It also revealed that none of the management practices evaluated, namely mineral fertiliser use, crop residue retention, and plant biomass addition, were enough to prevent the decline in key soil chemical properties after 10 years of cultivation of a Ferralsol. During the depletion phase, the treatments in which crop residues were retained and that received weed biomass amendments produced significantly higher seed cotton and maize grain yields, with or without mineral fertiliser applications (cf. Figure 1, Table 3). Crop residue incorporation significantly affected cotton and maize yield with and without fertilisers during the depletion phase. Towards the end of the depletion phase (1976–1980), cotton and maize yields were very low without residue incorporation, irrespective of mineral fertiliser use. During the regeneration phase, treatments that had received 10 t ha^{-1} year^{-1} of plant biomass during the depletion phase continued producing comparable cotton and maize yields without showing any significant difference due to mineral fertiliser use (cf. F0c vs. F1c in Table 3). In other words, yields could be maintained over 20 years with crop residue incorporation and weed biomass additions, without mineral fertiliser use, which led to low agronomic use efficiencies of the applied nutrients (Fig. 2). In the following sections, we examine the main trends observed in our results in the light of the existing literature.

Limited effects of combined organic inputs and mineral fertilisers on yield

Our results showed a neutral and occasionally positive effect of combining mineral fertiliser and organic resources application on cotton and maize yields. During the depletion phase, cotton and maize yields were increased and maintained only in treatments that retained crop residues and added weed biomass (F0c and F1c), irrespective of fertiliser use in the case of cotton, and producing barely 300 kg ha^{-1} year^{-1} extra yield with fertilisers in the case of maize. The positive legacy effects of having retained crop residues and added weed biomass to the soil during the depletion phase, despite fertiliser use, still produced the highest yields during the regeneration phase. Similar results were reported in different environments (Koulibaly et al. 2015; Mtangadura et al. 2017; Cardinael et al. 2022; Laub et al. 2023). In a long-term experiment, Cardinael et al. (2022) showed that combining mineral and organic fertilisers allowed them to maintain or even increase maize yields. The effect was greater than the sole application of one of the two inputs, and the differences in the effectiveness of the treatments were seen in the long term (Laub et al. 2023). These authors explained the positive effects on yields by the increasing improvement in mineral nutrition of cotton and maize (notably N and P) with positive interactions between nutrient sources. This effect increased with the quality of the organic resource (Gram et al. 2020). Laub et al. (2023) reported that manure additions (1.2 t C ha^{-1} $year^{-1}$) with high rates of nitrogen addition (> 300 kg N ha^{-1} $year^{-1}$) made it possible to maintain crop yields over the long term. Detchinli and Sogbedji (2015) suggested that crop yields could be sustained with 75% mineral and 25% organic sources under rhodic Ferralsol in western African coastal areas.

In our study, however, the highest cotton or maize yields were obtained in treatments that received plant biomass additions, irrespective of fertiliser use (cf. Fig. 3, compare F0c vs. F1c). Thus, the present long-term study does not show positive interactions or synergies between organic and mineral fertilisers. In line with this, some studies reported even negative effects on yield when combining organic resources with mineral fertiliser. For example, Chivenge et al. (2009) showed negative interactions with the combined use of organic and mineral fertilisers in the central region of Kenya due to the high fertiliser N content in the organic resources. High-nitrogen organic resources should not be used with nitrogen fertilisers, but the combination is still important for organic resources of low or medium quality. In our study, the similar yields between F0c and F1c can also be explained by sufficient nitrogen supply through biomass application, suggesting a sub-utilization of the applied mineral fertiliser-N (Mtangadura et al. 2017; Ndung'u et al. 2021). Although we lack information on the type of weeds that were present in the weed biomass that was added during the experiment, grasses such as *Imperata cylindrica* (Beauv.) L. which are common in this region of Benin may contain substantial amounts of phosphorus (e.g. 0.14%—Heuzé et al. 2016).

Yields decreased rapidly for treatment F0a during the depletion phase. During the regeneration phase, yields in the former treatments F0a, F0b, F1a, and F1b increased over 10 years but failed to achieve the yields obtained with the initial F1c and F0c treatments. This gap is what we term the 'soil's memory,' the legacy effect that prevents a complete regeneration of the productivity of soils that underwent severe degradation. Many authors have demonstrated the theoretical basics of the concept of soil memory as a soil capacity to record the environmental factors and soil-forming processes in a set of stable features in the solid phase of the soil body (Lapsansky et al. 2016; Targulian and Bronnikova 2019; Martínez-Fernández et al. 2021). The observed yield trends for cotton and maize across the depletion and regeneration phases highlight the complex interactions between soil fertility management practices, nutrient availability, and soil memory effects. Incorporating organic amendments (crop residues and weed biomass) played a crucial role in maintaining or even improving yield. However, long-term SOM trends do not show this (cf. Fig. 4a). In other long-term studies in West Africa, the combined use of organic inputs and mineral fertilisers was shown to enhance crop productivity, and this has been ascribed to improvements in nutrient synchrony and soil structure (Cardinael et al. 2022; Laub et al. 2023). In our study, continuous tillage could have accelerated SOM mineralization and nutrient leaching, reducing the long-term benefits of organic amendments (Six et al. 2002).

High biomass inputs boosted nutrient productivity but reduced fertiliser use efficiency

Organic resources positively influenced the factor productivity of N, P, and K, particularly in cotton. During the depletion phase, the highest nutrient productivity was recorded under treatment F1c, where mineral fertiliser application was coupled with incorporating crop residues and adding 10 t ha^{-1} $year^{-1}$ of weed biomass. This suggests that incorporating organic matter, alongside mineral fertilisation enhances nutrient availability and uptake. However, in treatments with high biomass application (10 t ha^{-1} weed biomass per year, F1c), the contribution of chemical fertiliser to yield was minimal, as reflected by the low agronomic nutrient use efficiency in these treatments. This indicates that the availability of nutrients from organic matter reduced the incremental yield response to mineral fertilisers. Therefore, large amounts of mineral inputs may lead to nutrient saturation and declining marginal returns in systems with large organic matter inputs. Also, in the studies by Cardinael et al. (2022) and Laub et al. (2023), the results indicate a diminishing influence of mineral fertiliser on nutrient factor productivity in treatments with high levels of organic inputs. The low agronomic nutrient use efficiency computed for treatment F1c in our study may also be explained by yields being limited by another factor, such as water availability, given the high variability in average yields between years.

The nutrient factor productivity (NFP) increased during the depletion phase, followed by stability in the regeneration phase, suggests that the applied mineral fertilisers and organic residues were efficiently utilized in the earlier years. However, the lack of further improvements in the regeneration phase raises critical concerns about nutrient factor productivity over time. The Ferralsols in the study area are highly weathered and prone to leaching. Over time, applied N, P, and K may have been lost due to high rainfall and poor cation exchange capacity (CEC), reducing their long-term availability. Given the observed decline in soil organic carbon, it is likely that reduced microbial activity, affecting nutrient availability to crops. The agronomic use efficiency (AE) of N, P, and K exhibited a significant treatment effect during the depletion and regeneration phases. While incorporating crop residues and weed biomass (Fb and Fc treatments) positively influenced nutrient availability, these treatments showed a decrease in AE compared to Fa. This reduction in AE is likely due to the higher nutrient supply from organic inputs in Fb and Fc, which diminished the marginal response to additional nutrient inputs, highlighting a trade-off between nutrient availability and use efficiency. One potential explanation for the decline in AE during the regeneration phase could be the increased mineralization of organic matter due to continuous tillage, which may lead to a faster release of nutrients and a reduction in their synchrony with crop uptake (Yansheng et al. 2020; Cao et al. 2021). According to the evolution of SOC during the experiment, the mineralization of soil organic matter decreased, being lower during the regeneration phase than the depletion phase in F1c treatments. In the other treatments, mineralization increased in the regeneration phase due to increased organic matter inputs. Additionally, the decrease in AE for Fa and Fb treatments was due to a huge increase in nutrient inputs from organic matter during the regeneration phase. The decrease in AE for Fc treatments associated with a decrease in crop yields during the regeneration phase is not explained by any variable measured or presented in this study.

These patterns suggest that while the initial depletion phase facilitated high nutrient use efficiency, prolonged soil exploitation without sufficient organic matter replenishment led to reduced fertiliser efficiency. The declining AE in the regeneration phase indicates that crops no longer responded efficiently to mineral inputs. This could be due to nutrient imbalances, soil structural degradation, microbial dysregulation, soil organic matter decomposition, and nutrient synchrony. The rapid mineralization of organic inputs in tropical climates can lead to a mismatch between nutrient release and crop uptake, reducing AE over time (Six et al. 2002). To address this challenge, integrating slow-release organic amendments (e.g., compost, biochar) and minimum tillage could enhance nutrient use efficiency and prolong soil fertility.

Soil fertility declined in the long term despite high organic inputs

The rapid mineralization of organic matter in a Ferralsol, driven by the warm, humid climate of the study site and the large sand content of the soil, likely enhanced nutrient cycling and contributed to SOC depletion across treatments (Yemadje et al. 2016). This high mineralization rate minimized the differences in SOC levels between treatments, indicating that maintaining SOC under such conditions remains challenging despite adding organic inputs. The observed consistent decrease in soil organic carbon (SOC) and nitrogen (N) during the depletion phase, followed by a stabilization during the regeneration phase, is a critical finding that was also observed in previous studies in the region (Kintché et al. 2010, 2015). The stabilization of SOC and N at very low levels during the regeneration phase indicates that the applied amendments were insufficient to rebuild soil organic matter stocks. This aligns with findings from long-term studies in SSA, where Ferralsols exhibit high carbon turnover rates, requiring continuous organic inputs for SOM maintenance (Tittonell and Giller 2013). Other soil chemical properties varied across treatments and phases. Higher exchangeable K, Mg, P, and CEC levels were observed in treatments that combined crop residue maintenance and weed biomass incorporation (F0c and F1c). Yet the final soil fertility status declined compared to the initial for all treatments. This suggests that the organic and mineral inputs applied were not sufficient to maintain soil fertility and nutrient status, probably due to continuous tillage (Dossouhoui et al. 2025). Conservation agriculture (based on minimum or no tillage, permanent soil coverage, and crop diversification) was shown to improve soil chemical properties and organic carbon in the sub-Sahara context (Corbeels et al. 2019; Sithole and Magwaza 2019). Interestingly, potassium (K), magnesium (Mg), and calcium (Ca) initially increased before declining in the regeneration phase. This trend could be explained by the fact that during the depletion phase, weathering and fertiliser applications may have increased the availability of exchangeable (Six et al. 2002). However, continuous cropping, leaching, and lack of organic matter replenishment likely led to subsequent declines. The depletion of SOC may have reduced soil CEC, limiting the soil's ability to retain essential cations over time.

Study limitations and further research

Despite the various insights that can be derived from this long-term study, some limitations still need to be highlighted. The study focuses on the effect of organic and chemical nutrients on crop production without considering the potential or water-limited yield levels in each situation. In fact, nutrient uptake rates are high under high-yielding environments (high radiation, optimal temperature, and no water limitations), and nutrient-limited growth is more likely to occur. The absence of seasonal water data matching the seasons of this study limits the full interpretation of the observed effects. Future studies should investigate the interaction between water availability and fertilisation strategies to better understand the factors driving yield responses in such systems over long periods, as such information is lacking in Benin. The study shows that plant biomass additions (crop residues and weed biomass) were sufficient to sustain crop productivity over time, even without mineral fertilisers and under conventional tillage. However, the feasibility of treatments that plough 10 t ha^{-1} $year^{-1}$ of weed biomass into the soil seems unrealistic in smallholders' farms, where biomass and labour are scarce, associated with limited land availability, low plant productivity, and adverse climatic conditions (Srivastava et al. 2017; Taveira et al. 2019).

The experiment was established on a former oil palm plantation field, and we have no information about the management and productivity of this previous crop. Oil palm plantations generally lead to high soil heterogeneity due to high input use and the residual root biomass that remains in the soil after plot clearance. Although we lack any soil or fertilisation data from the palm plantation, it is possible to speculate that nutrient additions were regular, and this may have had a legacy effect on subsequent cotton and maize during the depletion phase allowing, for example, to maintain crop yields in treatments with relatively low nutrient additions.

The value of the old study analysed here resides in the longitudinal combination of depletion and regeneration phases, with continuous annual ploughing as smallholder farmers do. However, nowadays, it is well known and documented that to mitigate the decline in nutrient use efficiency and soil fertility, strategies such as reduced or no tillage, incorporation of cover crops, animal manure, and agroforestry practices can be considered to improve crop yield, reduces variability and economic risks in cotton–maize rotations, and enhance nutrient cycling and carbon sequestration (Lal 2015; Atakoun et al. 2023; Akplo et al. 2025; Yemadje et al. 2025a, b).

Despite the age of the experiment, the dataset offers critical longitudinal insights into soil fertility trends and legacy effects in a context that remains highly relevant. Many smallholder farming systems in West Africa continue to operate under similar conditions of limited inputs, biomass scarcity, and annual tillage. Therefore, the findings contribute to understanding long-term soil responses to nutrient mining and rehabilitation-knowledge that can guide regenerative practices even in modern conservation agriculture frameworks.

Conclusions

This study illustrates that soils subject to prolonged fertility depletion develop long-lasting limitations to productivity, even when rehabilitation inputs are later applied. The persistence of these "soil memory" effects, particularly under conventional tillage, suggests that regenerative interventions must begin before critical thresholds of degradation are crossed.

Our findings challenge the prevailing assumption that combining organic and mineral fertilisers always results in synergistic benefits. In high-biomass treatments, mineral inputs offered little added value, raising concerns about input redundancy and efficiency. This has implications for resource allocation in smallholder systems where both biomass and fertiliser are scarce.

Given the limited recovery of soil organic carbon and nutrient stocks, even with substantial organic inputs, future research should explore conservation practices that stabilise organic matter, such as minimum tillage, cover cropping, and strategic legume integration. Additionally, long-term trials that include soil biological and physical indicators are essential to fully capture the multidimensional nature of soil restoration. Investments in archiving, digitising, and revisiting historical field trials can yield vital insights into long-term soil processes that remain invisible in short-term studies.

Acknowledgements The authors are very grateful to all the technicians who managed the experimental sites for an extended period and collected data about crop yields and soil. We also thank N. Goumissi for her valuable support.

Author contribution PLY: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing—review and editing—original draft. IA: Conceptualization, Methodology, Review and editing. RL: Methodology, review and editing. MC: Conceptualization, Writing—review and editing, Supervision. HK: Methodology, Writing—review and editing. AMA: Methodology, Writing—review and editing. KF: Methodology, Writing—review and editing, Supervision. SD: Methodology, Writing—review and editing, Supervision, ES: Methodology, Writing—review and editing, Supervision. PL: Methodology, Writing—review and editing, Supervision, PT: Methodology, Review and editing, Supervision.

Funding Open access funding provided by CIRAD.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Akplo TM, Yemadje PL, Imorou L, Sanni B, Boulakia S, Sekloka E, Tittonell P (2025) Minimum tillage reduces variability and economic risks in cotton–maize rotations in Northern Benin. Field Crops Res 324:109795. https://doi.org/10.1016/j.fcr.2025.109795

Atakoun AM, Tovihoudji PG, Diogo RVC, Yemadje PL, Balarabe O, Akponikpè PBI, Sekloka E, Hougni A, Tittonell P (2023) Evaluation of cover crop contributions to conservation agriculture in northern Benin. Field Crops Res 303:109118. https://doi.org/10.1016/j.fcr.2023.109118

Azontondé HA, Igue M, Dagbénonbakin G (2010) Carte de fertilité des sols du Bénin par zone agroécologique. Afrique-étude/INRAB

Boko M (1992) Saisons et types de temps au Bénin: analyse objective et perceptions populaires. Espace Geogr 21:321–332

Cao Y, He Z, Zhu T, Zhao F (2021) Organic-C quality as a key driver of microbial nitrogen immobilization in soil: a meta-analysis. Geoderma 383:114784. https://doi.org/10.1016/j.geoderma.2020.114784

Cardinael R, Guibert H, Kouassi Brédoumy ST, Gigou J, N'Goran KE, Corbeels M (2022) Sustaining maize yields and soil carbon following land clearing in the forest–savannah transition zone of West Africa: results from a 20-year experiment. Field Crops Res 275:108335. https://doi.org/10.1016/j.fcr.2021.108335

Chivenge P, Vanlauwe B, Gentile R, Wangechi H, Mugendi D, van Kessel C, Six J (2009) Organic and mineral input management to enhance crop productivity in Central Kenya. Agron J 101:1266–1275. https://doi.org/10.2134/agronj2008.0188x

Chivenge P, Vanlauwe B, Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Soil 342:1–30. https://doi.org/10.1007/s11104-010-0626-5

Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res 188:16–26. https://doi.org/10.1016/j.still.2018.02.015

Detchinli KS, Sogbedji JM (2015) Yield performance and economic return of maize as affected by nutrient management strategies on Ferralsols in Coastal Western Africa. Eur Sci J 11 No.27 ISSN: 1857–7881

Dossouhoui GA, Yemadje PL, Berre D, Diogo RVC, Tittonell P (2025) Understanding farm-level diversity to guide soil fertility management in West African cotton systems: evidence from Benin. Agric Ecosyst Environ 392:109749. https://doi.org/10.1016/j.agee.2025.109749

Gram G, Roobroeck D, Pypers P, Six J, Merckx R, Vanlauwe B (2020) Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: a meta-analysis. PLoS ONE 15:e0239552. https://doi.org/10.1371/journal.pone.0239552

Heuzé V, Tran G, Baumont R, Bastianelli D (2016) Alang-alang (Imperata cylindrica). Feedipedia, a programme by

INRA, CIRAD, AFZ and FAO. http://www.feedipedia.org/node/425
Huang X, Terrer C, Dijkstra FA, Hungate BA, Zhang W, Van Groenigen KJ (2020) New soil carbon sequestration with nitrogen enrichment: a meta-analysis. Plant Soil 454:299–310. https://doi.org/10.1007/s11104-020-04617-x
Kaur K, Kapoor KK, Gupta AP (2005) Impact of organic manures with and without mineral fertilizers on soil chemical and biological properties under tropical conditions. J Plant Nutr Soil Sci 168:117–122. https://doi.org/10.1002/jpln.200421442
Khan SA, Mulvaney RL, Ellsworth TR, Boast CW (2007) The myth of nitrogen fertilization for soil carbon sequestration. J Environ Qual 36:1821–1832. https://doi.org/10.2134/jeq2007.0099
Kidane W, Maetz M, Dardel P (2006) Food security and agricultural development in sub-Saharan Africa. FAO, Subregional Office for Southern and East Africa, Rom. ISBN 92-5-105544-0
Kintché K, Guibert H, Sogbedji JM, Levêque J, Tittonell P (2010) Carbon losses and primary productivity decline in savannah soils under cotton-cereal rotations in semiarid Togo. Plant Soil 336:469–484. https://doi.org/10.1007/s11104-010-0500-5
Kintché K, Guibert H, Sogbedji JM, Levêque J, Bonfoh B, Tittonell P (2015) Long-term mineral fertiliser use and maize residue incorporation do not compensate for carbon and nutrient losses from a Ferralsol under continuous maize–cotton cropping. Field Crops Res 184:192–200. https://doi.org/10.1016/j.fcr.2015.04.019
Kouelo AF, Mathieu AF, Julien A, Moriaque AT, Lambert A, Socrate AM, Pascal H, Anastase AH, Lucien AG, Aliou S (2020) Variation of physical and chemical properties of soils under different cropping systems in the watershed of Kpocomey, Southern Benin. Open J Soil Sci 10:501–517. https://doi.org/10.4236/ojss.2020.1011026
Koulibaly B, Dakuo D, Traoré O, Ouattara K, Lompo F (2017) Long-term effects of crops residues management on soil chemical properties and yields in cotton–maize–sorghum rotation system in Burkina Faso. J Agric Ecol Res Int 10:1–1131178. https://doi.org/10.9734/JAERI/2017/31178
Koulibaly B, Dakuo D, Ouattara A, Traoré O, Lompo F, Zombré PN, Yao-Kouamé A (2015) Effets de l'association du compost et de la fumure minérale sur la productivité d'un système de culture à base de cotonnier et de maïs au Burkina Faso. Tropicultura 33(2):125–134
Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustainability 7:5875–5895. https://doi.org/10.3390/su7055875
Lapsansky ER, Milroy AM, Andales MJ, Vivanco JM (2016) Soil memory as a potential mechanism for encouraging sustainable plant health and productivity. Curr Opin Biotechnol 38:137–142. https://doi.org/10.1016/j.copbio.2016.01.014
Laub M, Corbeels M, Mathu Ndungu S, Mucheru-Muna MW, Mugendi D, Necpalova M, Van de Broek M, Waswa W, Vanlauwe B, Six J (2023) Combining manure with mineral N fertilizer maintains maize yields: evidence from four long-term experiments in Kenya. Field Crops Res 291:108788. https://doi.org/10.1016/j.fcr.2022.108788
Martínez E, Maresma A, Biau A, Cela S, Berenguer P, Santiveri F, Michelena A, Lloveras J (2017) Long-term effects of mineral nitrogen fertilizer on irrigated maize and soil properties. Agron J 109:1880–1890. https://doi.org/10.2134/agronj2017.01.0020
Martínez-Fernández J, González-Zamora A, Almendra-Martín L (2021) Soil moisture memory and soil properties: an analysis with the stored precipitation fraction. J Hydrol 593:125622. https://doi.org/10.1016/j.jhydrol.2020.125622
Micheni AN, Kihanda FM, Warren GP, Probert ME (2004) Testing the APSIM model with experimental data from the long-term manure experiment at Machang's (Embu), Kenya. In: ACIAR proceedings, pp 110–117. ACIAR; 1998
Mtangadura TJ, Mtambanengwe F, Nezomba H, Rurinda J, Mapfumo P (2017) Why organic resources and current fertilizer formulations in Southern Africa cannot sustain maize productivity: evidence from a long-term experiment in Zimbabwe. PLoS ONE 12:e0182840. https://doi.org/10.1371/journal.pone.0182840
Mupangwa W, Thierfelder C, Cheesman S, Nyagumbo I, Muoni T, Mhlanga B, Mwila M, Sida TS, Ngwira A (2020) Effects of maize residue and mineral nitrogen applications on maize yield in conservation-agriculture-based cropping systems of Southern Africa. Renew Agric Food Syst 35:322–335. https://doi.org/10.1017/S174217051900005X
Ndung'u M, Ngatia LW, Onwonga RN, Mucheru-Muna MW, Fu R, Moriasi DN, Ngetich KF (2021) The influence of organic and inorganic nutrient inputs on soil organic carbon functional groups content and maize yields. Heliyon 7:e07881. https://doi.org/10.1016/j.heliyon.2021.e07881
Ripoche A, Crétenet M, Corbeels M, Affholder F, Naudin K, Sissoko F, Douzet J-M, Tittonell P (2015) Cotton as an entry point for soil fertility maintenance and food crop productivity in savannah agroecosystems–evidence from a long-term experiment in southern Mali. Field Crops Res 177:37–48. https://doi.org/10.1016/j.fcr.2015.02.013
Sithole NJ, Magwaza LS (2019) Long-term changes of soil chemical characteristics and maize yield in no-till conservation agriculture in a semi-arid environment of South Africa. Soil Tillage Res 194:104317. https://doi.org/10.1016/j.still.2019.104317
Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176. https://doi.org/10.1023/A:1016125726789
Srivastava AK, Mboh CM, Gaiser T, Ewert F (2017) Impact of climatic variables on the spatial and temporal variability of crop yield and biomass gap in sub-Saharan Africa: a case study in Central Ghana. Field Crops Res 203:33–46. https://doi.org/10.1016/j.fcr.2016.11.010
Tang B, Rocci KS, Lehmann A, Rillig MC (2023) Nitrogen increases soil organic carbon accrual and alters its functionality. Glob Change Biol 29:1971–1983. https://doi.org/10.1111/gcb.16588
Targulian VO, Bronnikova MA (2019) Soil memory: theoretical basics of the concept, its current state, and prospects for development. Eurasian Soil Sci 52:229–243. https://doi.org/10.1134/S1064229319030116

Taveira LRS, de Carvalho TS, Teixeira AFS, Curi N (2019) Sustainable productive intensification for family farming in developing tropical countries. Ciênc E Agrotecnologia 43:e012819. https://doi.org/10.1590/1413-7054201943012819

Tittonell P, Giller KE (2013) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res 143:76–90. https://doi.org/10.1016/j.fcr.2012.10.007

Tittonell P, Corbeels M, van Wijk MT, Giller KE (2010) Field—a summary simulation model of the soil–crop system to analyse long-term resource interactions and use efficiencies at farm scale. Eur J Agron 32:10–21. https://doi.org/10.1016/j.eja.2009.05.008

Tully K, Sullivan C, Weil R, Sanchez P (2015) The state of soil degradation in sub-Saharan Africa: baselines, trajectories, and solutions. Sustainability 7:6523–6552. https://doi.org/10.3390/su7066523

Vanlauwe B, Six J, Sanginga N, Adesina AA (2015) Soil fertility decline at the base of rural poverty in sub-Saharan Africa. Nat Plants 1:1–1. https://doi.org/10.1038/nplants.2015.101

Vanlauwe B, Kihara J, Chivenge P, Pypers P, Coe R, Six J (2011) Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339:35–50. https://doi.org/10.1007/s11104-010-0462-7

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29

Xin X, Zhang J, Zhu A, Zhang C (2016) Effects of long-term (23 years) mineral fertilizer and compost application on physical properties of fluvo-aquic soil in the North China Plain. Soil Tillage Res 156:166–172. https://doi.org/10.1016/j.still.2015.10.012

Yansheng C, Fengliang Z, Zhongyi Z, Tongbin Z, Huayun X (2020) Biotic and abiotic nitrogen immobilization in soil incorporated with crop residue. Soil Tillage Res 202:104664. https://doi.org/10.1016/j.still.2020.104664

Yemadje PL, Guibert H, Chevallier T, Deleporte P, Bernoux M (2016) Effect of biomass management regimes and wetting-drying cycles on soil carbon mineralization in a Sudano-Sahelian region. J Arid Environ 127:1–6. https://doi.org/10.1016/j.jaridenv.2015.10.017

Yemadje PL, Akplo TM, Imorou L, Sekloka E, Tittonell P (2025a) No-tillage and intercropping improve the yield and profitability of maize-cotton rotations in Northern Benin. Exp Agric. https://doi.org/10.1017/S0014479725100136

Yemadje PL, Tovihoudji PG, Koussihouede H, Imorou L, Balarabe O, Boulakia S, Sekloka E, Tittonell P (2025b) Reducing initial cotton yield penalties in a transition to conservation agriculture through legume cover crop cultivation-evidence from Northern Benin. Soil Tillage Res 245:106319. https://doi.org/10.1016/j.still.2024.106319

Zhong W, Gu T, Wang W, Zhang B, Lin X, Huang Q, Shen W (2010) The effects of mineral fertilizer and organic manure on soil microbial community and diversity. Plant Soil 326:511–522. https://doi.org/10.1007/s11104-009-9988-y