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Unravelling sustainable intensification in oil-palm agroforestry on the Adja plateau, Benin

Rolland H. Yemadje · Hermione Koussihouèdé · Sylvain Rafflegeau

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Abstract Pathways for mediating the competing land-use claims of landowners and tenants in oil palm agroforestry systems in Benin's Adja plateau do not consider the diversity of land-management practices. Therefore, we analysed how soil properties and maize yields in those systems are affected by two contrasting categories of land-management practices and fertilisation options. We used a synchronic approach to split these practices and options into two successive steps. In Step 1, referred to as cropped fields, tenants continuously intercrop maize among scattered oil palms. In Step 2, referred to as fallows, the land is densely planted with oil palm, without intercropping. Twelve farmers' fields were selected for this study. Eight represent cropping fields, and four are 15-year-old oil-palm fallows. Cropped field fertilisation treatments consisted of farmyard manure (at 15 and 30 t ha^{-1}) and mineral fertiliser (150 kg ha^{-1} of $N_{14}P_{18}K_{18}S_6B_1$ + 50 kg ha^{-1} of urea). We found no significant differences between the N contents and C:N ratios of the two types of fields. However, the numbers and masses of earthworm casts were higher in cropped fields treated with farmyard manure than with mineral fertiliser. Farmyard manure (15 and 30 t ha^{-1} rates) also produced significantly higher maize yields (respectively, 2.5 and 3.2 t ha^{-1}) than the mineral fertiliser alone (1.9 t of maize per ha). We conclude by discussing N, K and P storage in soil, and recommended use of farmyard manure as an agroforestry practice that will benefit landowners and tenants alike on the Adja plateau.

Keywords Competing claims · Earthworms · Fallow · Maize · Oil-palm agroforestry · Organic matter · Sustainable intensification

Introduction

Sustainable intensification, coined as the *richer shade of green* by Struik and Kuyper (2017), suggests that

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R. H. Yemadje (✉)
Soil Biology Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
e-mail: rolandyemadje@gmail.com

R. H. Yemadje
Knowledge, Technology and Innovation Group, Wageningen University, Wageningen, The Netherlands

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

S. Rafflegeau
CIRAD, UMR INNOVATION, 34398 Montpellier, France

S. Rafflegeau
INNOVATION, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France

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agricultural production should safeguard not only socio-economical equity but also trade-offs between short and long-term practices.

Intensification of agroforestry systems has been sustained over time through trade-offs between fallows and cropping practices (Vaast and Somarriba 2014; Visscher et al. 2021). However, divergent effects are reported for intensification practices (such as combining mineral and organic fertiliser), depending upon organic matter quality, the rate, and the land-use system (Chivenge et al. 2011).

On the Adja plateau in southwestern Benin, the primary land-use system is oil-palm (*Elaeis guineensis Jacq*) agroforestry, in which palms (local *dura*-variety) are combined with food crops such as maize, yams, cassava, beans, sorghum, rice, and vegetables (Igue et al. 2000). The unselected palms are tapped to produce local brandy (*sodabi*) from the sap. In contrast, the small-scale intercropped oil-palm cropping system that prevails in south central Benin is mainly dedicated to oil production, and planted at a density of 143 selected palms per ha (Koussihouede et al. 2020; Masure et al. 2022). The agroforestry system on the Adja plateau is divided into two successive steps. Step 1 (a in Fig. 1) consists of fields in which food crops grow among the sparse plantings of young oil palms (50–60 palms per ha). Step 2 (b in Fig. 1) is a pure, dense stand of palms (400–1600 per ha) without crops. In this step, the oil palms act as a productive, planted fallow known as *dekan*. Each of the steps is managed by different socio-institutional groups: tenants and landowners (Koudokpon et al. 1994; Yemadje et al. 2012). Landowners hold the title to land that contains the oil-palm stand (Step 2). In Step 1, during which the palms are not generating revenue, landowners lease the land to tenants, thus allowing them to produce food crops against a part of the food crop production. Typically, tenants can grow crops until the oil palm crown reaches a

Fig. 1 Pictures of the oil palm agroforestry systems on the Adja plateau. Step 1. **a** Cropped fields with high input of mineral fertilisers, with young *dura*-variety pruned palms; and Step 2. **b** A 15-year-old *dura*-variety oil palm fallow with no fertiliser input

height of two metres—which takes about 15 years due to root damage and palm pruning (Koudokpon et al. 1994). During that time, tenants apply organic fertilisers [mainly farmyard manure (FYM)] and mineral fertilisers (Inf) to food crops (Yemadje et al. 2014).

Even though tenants apply the fertilisers only intermittently, landowners claim that the intensive cropping depletes soil fertility. Therefore, landowners ultimately prefer to evict the tenants, and to leave the land in oil-palm fallow to replenish soil fertility. The result is conflicts over access to the land, due to competing claims of landowners and tenants, and between oil palms and annual food crops (Yemadje et al. 2014).

Much effort has been made in the Adja plateau to resolve these conflicts by implementing formal land titling to provide equitable access and secure tenure (Yemadje et al. 2014). However, those efforts did not take into consideration the diversity of land management practices; their respective ecological performances; and the role that those practices might play in providing acceptable trade-offs between fallows and cropping practices in this specific context.

For example, applications of organic amendments during Step 1 could mitigate the effects of increased usage of mineral fertiliser. More specifically, organic amendments could prevent the reduction in phosphorus (P) availability that occurs in acidic soils when mineral fertilisers are applied frequently (Gichangi 2019). The effects of field management practices (landowners' fallows, tenants' mineral fertilisation, and application of organic amendments) upon soil fertility in the context of oil-palm agroforestry have never been explicitly elaborated even though organic matter plays a key role in agricultural sustainability (Bationo et al. 2007; Chivenge et al. 2011), and earthworm activity is key to supporting soil organic matter (Saïdou et al. 2008; Whalen 2014). Information about effects upon soil organic carbon (C), soil chemicals (N, P, and K), and soil biological fertility (earthworm-cast density) could be especially important.

The overarching aim of this paper is to analyse the impacts of the combined use of organic and mineral fertilisers upon soil fertility and land productivity (yields per ha) to understand sustainable-intensification pathways in oil palm agroforestry on the Adja plateau. We examined the extent to which agricultural intensification practices (application of farmyard manure and mineral fertiliser) during Step 1 could replenish soil fertility and improve land productivity (or not) compared to the so called 15-year-old palm fallows.

Methodology

Study area

About 60% of Benin's 11.5 million inhabitants live in the south of the country (INSAE 2013), which is in the oil-palm agroforestry belt in West Africa's humid tropical zone. The study area covered the rural districts of *Klouekanme* and *Toviklin* on the Adja plateau in the *Couffo* department, southwestern Benin (Fig. 2). We used the transect method to select random plots and farmers in an area with homogeneous soil types and food crops (Yemadje et al. 2012). Thus, the experimental sites were in the villages of *Akouegbadja* and *Sognonnouhoue* along a mega-transect that is 10 km long and 0.5 km wide (Fig. 2). The transect is bounded to the northeast by the village of *Agbago* and to the southwest by the village of *Sognonnouhoue* (Fig. 2).

The region has a sub-humid tropical climate with bimodal rainfall distribution. Rainy seasons run from April to July and September to November. The long dry season lasts from December to March, and the short one from July to August. Average annual rainfall is 1200 mm (Alle et al. 2013). During the course of a year, the average temperature varies from 25 to 29 °C, and the relative humidity from 65 to 97% (Alle et al. 2013). Along our transect, the soils are homogeneous red ferralitic, classified as Ferralsols (FAO 1998) and as Eustrustox (USDA soil taxonomy). They formed on the sandy clay sediments of the Continental Terminal, and are well-drained and permeable, with moderately fertile upper layers (0–20 cm) containing on average 39 g kg^{-1} total C, 670 mg kg^{-1} N, 7.3 mg kg^{-1} P, 100% base saturation, and 5.3 cmol kg^{-1} CEC. Ferralsols are known to have a reasonable inherent chemical fertility (Igue et al. 2000).

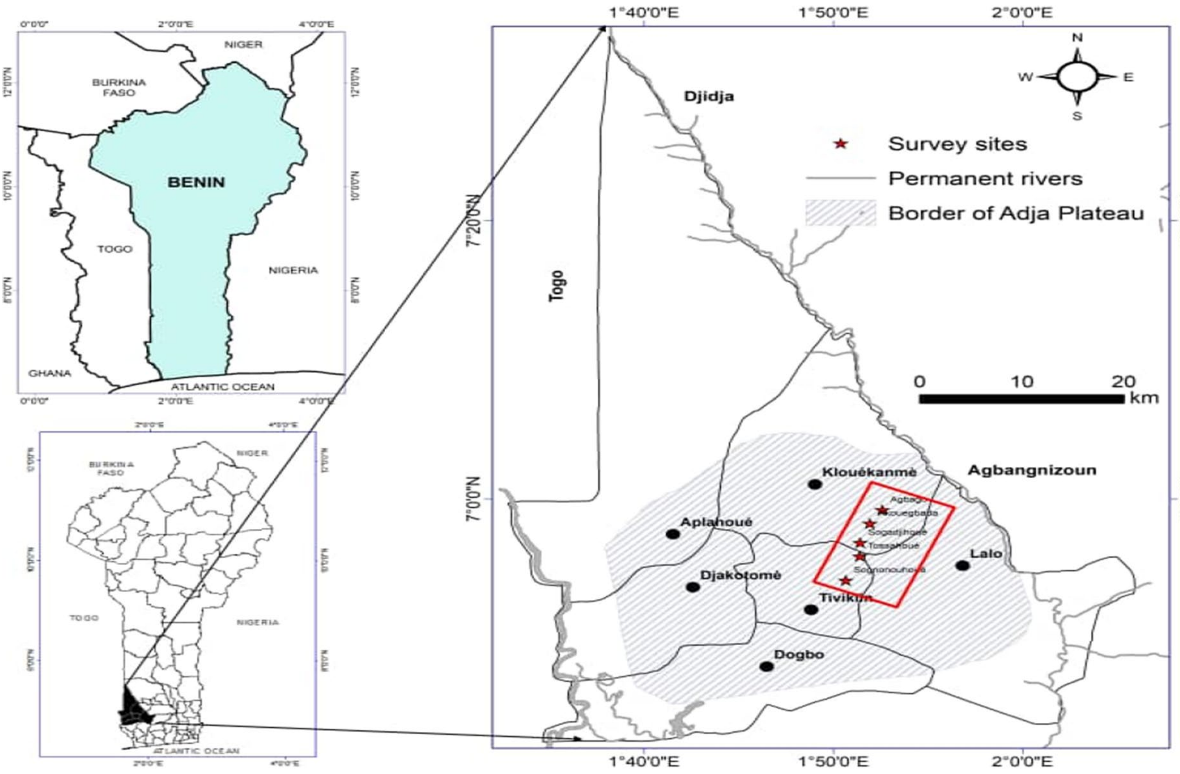

Fig. 2 Map showing the Adja plateau and the NE-SW study areas along a mega transect. The transect method allowed us to identify the 15-years-old oil palm fallows studied on a random basis

Experimental design

A synchronic experimental approach was implemented during the first cropping seasons (April–July) of the years 2010, 2011, and 2012. We selected 12 farmers' fields respecting the local proportions of cropping fields and fallow. Four fields were 15-year-old oil-palm fallows (typical of landowners' practices), and eight were cropped fields on which tenants used mineral and organic fertilisers. The cropped fields were selected based on similarities in fertiliser-management practices and cropping history. (See Supplementary Materials, Table S1). These fields had been cropped continuously with maize during the previous 5 years. They had received farmyard manure and mineral fertiliser regularly in the past (approximately 15 t ha^{-1} based on farmers' report), but no manure was applied at the beginning of the 2010 rainy season. In each field, we delineated a 250-m^2 main plot (corresponding to the cropped field average surface), which was selected to be as uniform as possible. (I.e., with a similar number and configuration of oil palms, and with no visible termite mounds, bumps, erosion bands, or colour differences.)

The main plot was then subdivided into six sub-plots of 36 m^2 (6 m×6 m), to which we applied six treatments covering the range of farmers' fertilisation practices that were found during a previous survey. The six treatments are:

- Control: No application of manure and mineral fertiliser;
- Inf: application of 150 kg NPKSB + 50 kg urea per ha;
- 1FYM: application of 15 t ha^{-1} (dry matter) of farmyard manure;
- 2FYM: application of 30 t ha^{-1} (dry matter) of farmyard manure;
- 1FYM + Inf: application of 15 t ha^{-1} (dry matter) and 150 kg NPKSB + 50 kg urea per ha of farmyard manure;

– 2FYM + Inf: application of 30 t ha^{-1} (dry matter) of farmyard manure and 150 kg NPKSB + 50 kg urea per ha.

This experimental design was replicated during 2011 and 2012 in the same fields. Farmyard manure was applied uniformly to the assigned subplots from January to March 2011 (thereby allowing three months of decomposition before the start of the cropping season). Surveys of the farmers had found that 15 t ha^{-1} is the common annual rate of farmyard manure application in their fields (Yemadje et al. 2014). The mineral fertiliser formula was $N_{14}P_{18}K_{18}S_6B_1$, which was chosen because it is the main fertiliser available in the area, and the one most used for cash crops such as tomatoes, cabbage, carrots, and lettuce. It was applied during each year's cropping seasons; half of the treatment (i.e., half of the 15 t ha^{-1} or 30 t ha^{-1}) was applied 25 days after sowing, and the other half at 45 days.

Farmyard manure characteristics

The farmyard manure was collected by tenant farmers from their eight selected fields, and used in those same fields. Typically, the farmyard manure in the studied villages consisted of 70% leguminous matter (cowpea pods, with C:N ratio = 17:1) and 30% non-leguminous remains of maize. The C:N ratios for those remains were 33:1 in stems; 32:1 in leaves; and 48:1 in roots. The manure had the appearance of a mixture of non-decomposed pods and straw. Because the practices of the selected farmers are similar, we assumed that all of the manure was identical.

Maize cultivation

The maize used in this trial was the local, medium-early *gbogbui* variety, which has a 90-day cycle. Crop-management practices were typical for maize on the Adja plateau: plots were sown using two seeds per hole, at inter- and intra-row spacings of 80 cm and 40 cm, respectively (approx. 31,250 plants per ha). The same batch of seed was used for all fields. Fields were sown in April, at the start of the rainy season. No thinning was done after germination. The ground was hoed twice: 10–15 days after sowing and 30–35 days after sowing. No pesticides were applied. The crop was harvested 85–90 days after emergence.

Measured variables

Soil properties

Composite soil samples were collected with an auger from the 0 to 20 cm topsoil layer in June 2010, April 2011, and May 2012. In 2010, one composite sample was taken per field before the delineation of the subplots. In 2011 and 2012, one composite sample was taken per subplot (treatment). Chemical analyses were conducted in the Laboratory of Soil, Water, and Environmental Sciences (LSSEE) of the National Institute of Agricultural Research of Benin (INRAB). Each sample was analysed for soil acidity (pH KCl), total N, organic C, available P, and exchangeable K.

The pH KCl was determined with a soil:water ratio of 1:2.5 with 1 g of KCl added to the soil:water suspension. The C contents were determined using the Walkley and Black (1934) spectrophotometric method, with a wavelength of 660 nm (nm). N contents were determined by the Kjeldahl method (Kjeldahl digestion in a mixture of H_2S0_4-selenium, followed by distillation and titration). The available P was extracted using the Bray 1 method, and assayed by colourimetry at a wavelength of 660 nm (Bray and Kurtz 1945). The exchangeable K was extracted with a neutral solution of ammonium acetate (Thomas 1982), and assayed by atomic-absorption spectrometry. Details on the state of the soil before the experiment are presented in the Supplementary Materials, Table S6.

Dynamic assessment of earthworm casts

During the 2012 cropping season, earthworm casts on the soil surface were counted and collected in each treatment subplot every 10 days for 40 days. More specifically, casts were counted on the same days in each field, beginning on 12 May (i.e., two weeks after sowing), and every ten days thereafter until 20 July. In each subplot, we delineated four quadrants for counting. Each of the quadrants represented a sampling unit (0.5 m × 0.5 m = 0.25 m^2), and was flagged and georeferenced. The collected casts were weighed after oven-drying for 48 h at 60 °C.

Yields of maize grain and straw

The treatment subplots were harvested approximately three months after sowing (85–90 days after emergence). In each subplot, we collected the maize spikes from all of the plants that had grown within the central 2 m × 2 m square. The maize spikes were then shelled to determine grain yields per ha. The shelled cobs and husks were added back to the remaining maize stalks, inflorescence, and leaves to determine straw yield per ha. Thus, the reported dry-matter yields of maize straw include maize stalks, leaves, inflorescence, shelled cobs, and husks. To determine the yields, representative samples of the grain and straw per ha were taken and weighed before and after being oven-dried at 60 °C for 72 h. Harvest indexes (HI) were calculated for each subplot as the ratio of grain yield to the sum of grain and straw yields (Fan et al. 2017).

Statistical analysis

All analyses of effects and dynamics were carried out with R software (R Core Team 2017), at 5% significance.

Analysis of effects of soil-fertility-management strategies upon soil and yield parameters

To test the fixed effects of soil-fertility-management strategies and the random effects of sites and years upon soil properties and maize yields, we used linear mixed-effect models, implemented via the R software packages 'lmerTest' (Kuznetsova et al. 2017) and 'MASS (Venables and Ripley 2002). In this analysis, the random factor "sites" was considered as nested within the random factor "years". The equation of the model is:

$$Y_{ij} = 0 + \ 1(\text{soil fertility management strategies}) + (\text{years/site})i + ij,$$

where the subscripts i and j on the Y axis indicate that each observation j is nested within the cluster (year/site)i; β_0 is the overall intercept; and ε_{ij} is the residual error.

Here, the intraclass correlation coefficient (ICC) determines between-years/sites variability, calculated as the ratio of between-years/sites variance to total variance, then multiplied by 100 to express it as a percentage.

Using the mixed model established in the package lmerTest, adjusted means were computed with the ''emmeans'' function of the emmeans R package based upon default parameters (Lenth 2018). When the fixed effect was significant (p value < 0.05), we computed the multiple comparisons of the levels of the fixed factor by using the Tukey HSD method (Graves et al. 2019) of the multcompView R package, with default parameters. In addition, a principal component analysis (PCA) in R's factoextra package (Kassambara and Mundt, 2020) was used to describe the relations between the soil parameters, and to characterise the different treatments.

Analysis of data on the dynamics of earthworm casts

The longitudinal data for the number and the mass of earthworm casts were modelled by using linear and generalised mixed-effect models, as implemented in the R package 'nlme' (Pinheiro et al., 2017). (See supplementary Table S2.) The modelling procedure consisted of successively testing the effect of the random factor (site) via the unconditional-mean model, and the effect of time via the unconditional-growth model. The contribution of the effects of site and time to total variability was assessed by calculating, respectively, the ICC and variability due to time. Based upon the evaluation of the effect of "treatment" (which was the factor of interest), we selected the best structure of variance–covariance matrices for the residuals, after testing the likelihood ratio. Using the same test, the selected model enabled us to choose the best structure of the matrix of random effects. That structure was then used to perform simple analyses of variance to assess the significance of treatment, time, and their interactions (p-value < 0.05). Finally, growth curves were built to describe the specifics of each treatment.

Results

Effect of farmyard manure and mineral fertiliser applications

Soil chemical nutrients

With the exception of soil C content, none of the soil chemical properties differed significantly across experimental treatments (p value > 0.05, see Supplementary Materials, Table S3 for model results). The first two axes of the PCA that was constructed for soil chemical properties across the treatments explained 82% of the total variance (see Supplementary Materials, Fig. S1). Axis 1 explained 52% of the variance, with P, K, and C:N being strongly correlated. Axis 2 explained 30% of the variance, with pH KCl, C, and N strongly correlated. The PCA score plot (Supplementary Materials, Fig. S1) showed that pH KCl, C, and N were highest in treatments with 30 t ha^{-1} of farmyard manure (2FYM and 2FYM + Inf). P and K concentrations were lowest in the control, and in treatments with either mineral fertiliser (Inf) or 15 t ha^{-1} of farmyard manure (1FYM). The treatment that combined 15 t ha^{-1} of farmyard manure and mineral fertiliser (1FYM + Inf) had the lowest C and N values. The correlation of each initial variable with the PCA axis is presented in Supplementary Materials, Table S4.

Dynamic of earthworm casts

The numbers and masses of earthworm casts varied significantly ($p < 0.05$) across treatments as well as with time of collection (i.e., days after sowing). The high ICC values for the factor *time* (67.2% for the number of casts, and 63.43% for mass) indicate that most of the between-treatments variability was attributable to the time of collection. In contrast, the ICC values for the variable *site* (0.001% for number of casts, and 23.83% for the mass) indicate that between-sites variability was high for the mass of earthworms (Supplementary Materials, Table S2). The numbers and masses of casts increased steadily with time in all six treatments (Supplementary Materials, Fig. S2). However, the numbers and masses were higher in the treatments with farmyard manure (1FYM and 2FYM) than for the control and the treatments with mineral fertiliser (Inf). In addition, during the first 30 days, the masses of earthworm castss were intermediate in plots that were treated with a combination of farmyard manure and mineral fertiliser (1FYM + Inf and 2FYM + Inf).

Maize grain and straw yields

The effects of treatments upon yields of grain and aboveground biomass were highly significant (p-value $<$ 0.05, see Supplementary Materials, Table S5 for model results). Between-treatments differences in HI were not significant (Fig. 3). The ICC values were 0.22% for grain yield, 0.001% for straw yield, and 36.78% for HI, indicating that the between-year/site variability was highest for HI. The average grain yield in the treatments with an application of 30 t ha^{-1} of farmyard manure (2FYM) was 35% higher than that in treatments with mineral fertiliser (Inf), and 60% higher than in the control. The average grain yields were intermediate in the other treatments (Fig. 3). Nevertheless, grain yield values associated with the application of 15 t ha^{-1} of farmyard manure in either treatment (1FYM and 1FYM + Inf) were on average 24% higher than those with mineral fertiliser (Inf). The average yields of straw in treatments that combined farmyard manure and mineral fertiliser (1FYM + Inf and 2FYM + Inf) were 40% higher than in treatments with mineral fertiliser (Inf) alone, and 48% higher than in the control. The other treatments gave intermediate yields. Yields of grain and straw in subplots that received the mineral fertilizer were not significantly different from those in the "control" subplots. (Fig. 3).

Farmyard manure and mineral fertiliser application versus fallows

In fallow-plot soils, the variations of chemical properties across treatments were highly significant (p value < 0.05) (Fig. 4). The ICC values were 34.47% for pH KCl; 24.01% for K; and 0.001% for C, N, P, and C:N, indicating that between-year/site variability was low for most properties. The average soil pH KCl was highest in the subplots where 30 t ha^{-1} of farmyard manure was applied (2FYM and 2FYM + Inf), and lowest in the fallows. Values were intermediate for the other treatments. The P content of soil was higher in all the treatments than in the fallows. A minimal p value of 24 mg kg^{-1} was found in the 1FYM subplots, whereas a value of only 7 mg kg^{-1} was found in the fallows. The average K content of soil in the 1FYM, 2FYM, and 1FYM + Inf subplots was three times higher than in the fallows, with intermediate values for the other treatments (Fig. 4). No significant differences were found between the compared items (treatments and fallows) for N, C, and C:N.

No significant difference was found for pH KCl, C, N, and C:N between the control (with no application

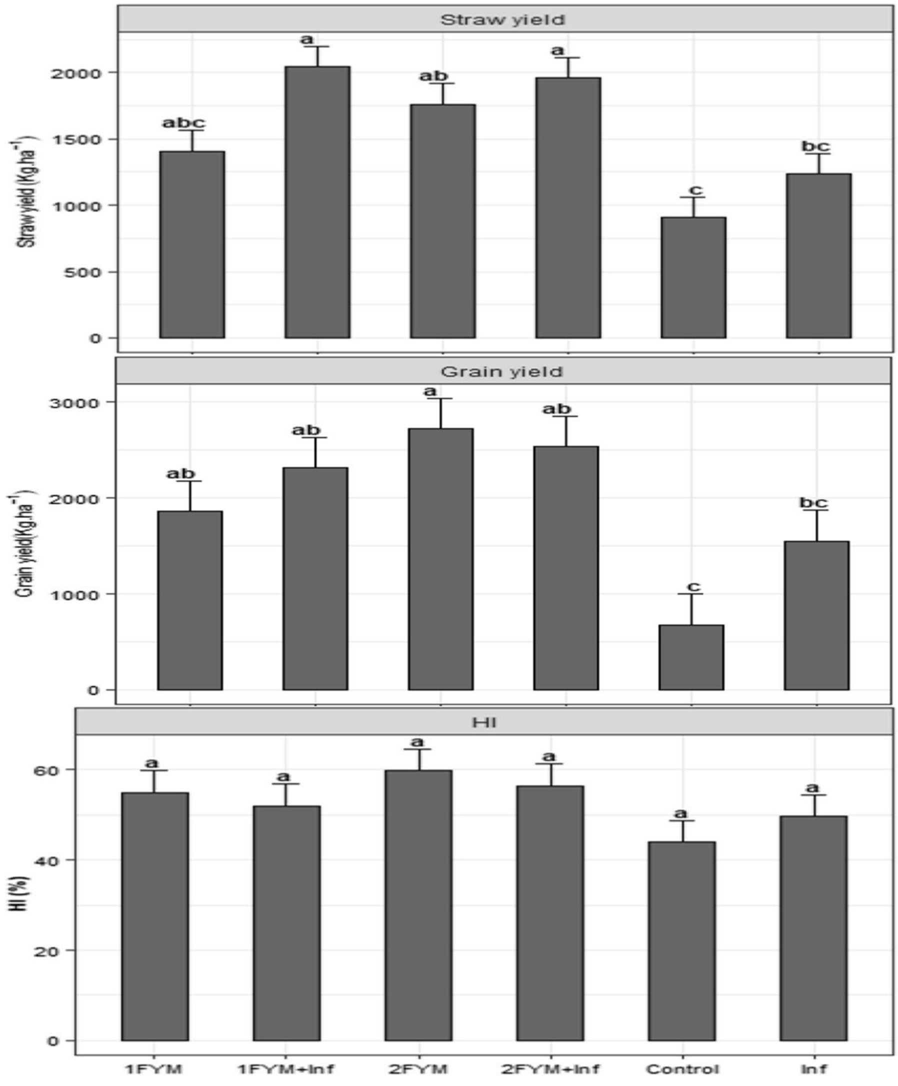

Fig. 3 Grain yields, straw yields, and harvest indexes (HI) for the six treatments. Means followed by same letter in each figure are not significantly different ($p < 0.05$). Bars are standard errors of the means

of farmyard manure or mineral fertiliser) and the fallows (p value > 0.05). Significant differences were found only for P and K, which were, respectively, 75% and 28% higher in the control (p value < 0.05) (Fig. 4).

Discussion

Cropped-field soils are richer in P and K than oil-palm fallows

P and K are higher in cropped field soils than in palm fallow soils, but total C and total N are the same. This result can be interpreted as an effect of fertilisation in cropped fields and/or the absence of an effect of fallowing, thanks to the high K uptake of the oil palms planted at very high densities in the fallows. Oil palms take up large amounts of K (Caliman et al. 1994) that are released from the oil palm residues within three months after the palm is stumped. Further studies could regularly assess the soil K content after all the tall palms are stumped down for palm-sap extraction (i.e., at the beginning of Step 1). Intensive cultivation does not seem to reduce the availability of plant nutrients. Therefore, our study does not give any support to Koudokpon et al.'s (1994) assertion that the soil nutrient balances between cropped fields and palm fallows in oil-palm agroforestry systems are highly negative. However,

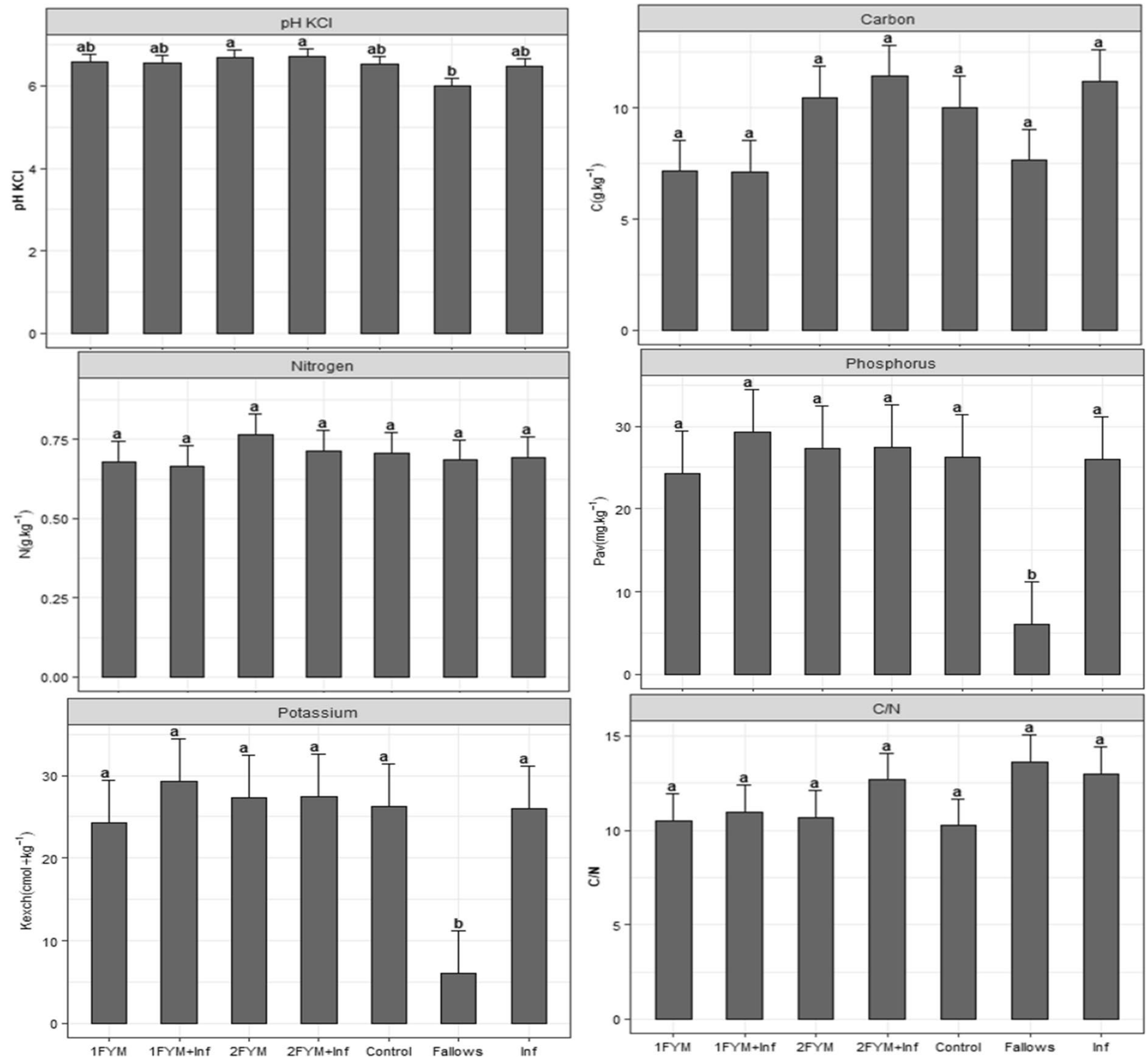

Fig. 4 Soil chemical properties (0–20 cm) in the treatments compared to the fallows. Means followed by same letter in each figure are not significantly different ($p < 0.05$). Bars are standard errors of the means

we did not calculate nutrient balances, and high P and K contents do not necessarily imply either a surplus or a positive nutrient balance. Landowners' perceptions that soil fertility is increased by long-term oil-palm fallowing probably results from the visible large stock of organic matter constituted by the oil-palm biomass under decomposition process. Benjaminsen et al. (2010) described the main mechanism in fallows as a comparatively slow transport of nutrients from the lower soil horizons to the upper.

Farmyard manure improved cropped soil fertility and maize yield fostering sustainable intensification

Indicators of soil chemical and biological properties showed the best performance in the soils that received applications of farmyard manure (with or without mineral fertilisers). These soils also had the best yields of maize grain and straw. The maize HI remained within the range of common values, as reported in Ion et al. (2015) for several growing conditions. This finding indicates that addition of farmyard manure was a valuable management practice for improving agricultural performance and maintaining soil fertility in the non-conventional oil-palm agroforestry system (Masure et al. 2022). Similarly, Vaast and Somarriba (2014) reported that additions of farmyard manure help to avoid sole mineral fertiliser intensification in cocoa agroforestry systems.

The differences in P and K contents and grain and straw yields between the two rates of manure application (1FYM + Inf and 2FYM + Inf) were not significant, suggesting that rates higher than 15−30 t ha^{-1} would not be very useful for increasing yields or further improving soil chemical properties. However, the PCA showed that C and N were lowest in the soil treated with 1FYM + Inf, and also that P and K concentrations were lowest in 1FYM. This finding suggests that the farmyard manure had not yet released all its nutrients, and is consistent with the observation that decomposition of the manure was still in progress due to the recalcitrance of the maize straws. Our results suggest that a rate as high as 15–30 t ha^{-1} of farmyard manure fostered earthworm activity. Similarly, Saïdou et al. (2008) found a high density of earthworm casts in maize fields in other regions of Benin. Along with earthworms, the soil microorganisms could act in the release of the nutrients in the farmyard manure, as suggested by Whalen (2014). Further studies are desirable to determine the diversity and dynamics of these organisms in our context of study.

Combining lower mineral fertiliser applications with farmyard manure for more sustainability

The most paradoxical result for the Adja plateau is that applications of mineral fertiliser did not increase yields of maize-grain appreciably. This observation suggests that for Adja-plateau soils, the currently recommended rate of 50 kg of urea and 150 kg ha^{-1} of NPK mineral fertiliser is not high enough to cause significant differences between the treated and control plots. Thus, there is reason to doubt that the recommended application rates of mineral fertiliser are adequate. However, our findings are tuned with Chivenge et al. (2011) suggesting that combining organic and low mineral fertilisers may offer an increased maize yield, nutrients efficiency, and residual effect. The combined use of mineral and organic fertilisers is based on two principles: (1) supplying the necessary quality and quantity of organic matter (involving the entire biogeochemical cycle, using earthworms and other microorganisms to break down organic matter for nitrogen mineralisation), and (2) synchronisation of available nitrogen and optimal crop need. Gentile et al. (2011) discussed the synchronisation, and mention it as the best way to temporarily immobilise nutrients for release at a later stage, thereby improving the fit between nutrient availability and crop demands. Residue quality and N-fertiliser application can therefore be manipulated to influence short- or long-term yield sustainability (Gentile et al. 2011) referred to as the *richer shade of green* by Struik and Kuyper (2017). Nevertheless, given the costs associated with the demand for labour (data not shown), the lack of any benefits from applying sole mineral fertilisers below this rate should be even more pronounced for maize yield. Thus, technical fertiliser recommendations for maize production in the Adja plateau need to promote combined organic and mineral fertilisation at rates whose benefits for fostering agriculture sustainability have been documented.

Conclusion

Our findings showed that applications of farmyard manure potentially enhance sustainable intensification of oil-palm agroforestry systems through better soil fertility and higher maize yield. Guaranteeing sustainability via this practice inevitably requires applying the manure at rates high enough to provide organic matter to maintain the biological activity of earthworms which maintains soil fertility. In the future, extension and research services should collaborate on documenting timely the match between the application rates of farmyard manure and mineral fertiliser.

In addition, application of farmyard manure is conducive to more social equity in between landowners and tenants. More specifically, the combined applications of farmyard manure and mineral fertiliser can solve the initial conflict between tenants and landowners over the loss of soil fertility consequent to tenant farmers' intensification of food-crop production during Step 1. With such a sustainable fertility management by tenants, landowners will probably have more vigorous palms, and therefore higher *sodabi* revenue. Likewise, the farmyard-manure application practice creates a win–win situation that makes cultivation more sustainable during both steps of the oil-palm agroforestry system. Both actors benefit from the resulting improvements in soil nutrients and land productivity. Therefore, application of farmyard manure is a socio-technical practice to achieve a beneficial trade-off between yield and soil fertility in the oil-palm agroforestry.

However, questions remain about the sustainability of the trade-off practice itself in an agroforestry context where labour is increasingly individualised, commodified, and therefore constraining. The mobilisation of a higher rate of farmyard manure (30 t ha^{-1})—and its application—remains a challenge in upscaling farmyard manure use. Therefore, governments should provide institutional flexibility regarding local practices such as farmyard manure application, to facilitate adaptive land governance.

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Data availability Supplementary tables have been provided.

Declarations

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