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Nutrient availability challenges the sustainability of low-input oil palm farming systems

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ABSTRACT

The social and economic benefits for smallholders cultivating oil palms are usually associated with environmental degradation and high resource consumption inherent to intensive farming systems. Nonetheless, the extensification of agricultural practices by many smallholders due to limited access to funds, agricultural inputs, or knowledge may result in a more environmental-friendly oil palm production. Here, we assessed the trade-offs between production and soil degradation in two oil palm farming systems established on forested land in the Ngwei region (Cameroon) comparing practices with no (smallholder system, SH) and low (elite system, EL) agricultural inputs (fertilizer, herbicides). Soil characteristics, nutrient deficiencies and oil palm production were determined in forty-two plantations of different age covering one full plantation cycle. The rates of soil organic carbon (SOC) loss were similar in both farming systems (-0.029 ± 0.012 kg C m^{-2} yr^{-1}), but soil bulk density and pH were not affected by the forest conversion. Soil available potassium (K) decreased sharply during the first 7.3 $\pm$ 0.9 years before stabilizing. Potassium fertilization limited leaflet K deficiencies during the immature phase in EL, but was not sufficient to prevent K deficiencies during the production phase, reaching similarly low K nutrition index as in SH (0.68 $\pm$ 0.13). Oil palm growth was similar in both systems, but fresh fruit bunches (FFB) production was enhanced by 38 $\pm$ 11% in EL. The nitrogen (N) deficiencies were pronounced in both systems. However, the higher biomass export in EL induced phosphorus depletion in soils and reinforced N depletion as compared to SH. Despite limited soil degradation, nutrient depletion in the agroecosystem threatens the sustainability of these two low-input oil palm farming systems. This calls for optimization, such as a targeted intensification in the EL system and a reduced oil palm density in the SH system.

1. Introduction

Oil palm is cultivated in tropical countries as cash crop by millions of smallholders, as well as in the form of industrial plantations operating at a much larger scale (Rist et al., 2010). The economic and livelihood benefits of oil palm cultivation need to be set against the often substantial environmental impacts resulting from the large-scale expansion of oil palm plantations in tropical forested areas (Grass et al., 2020). Deforestation and intensive cultivation practices have led to decreased ecosystem carbon storage (Guillaume et al., 2018), large greenhouse gas emissions (Meijide et al., 2020), soil degradation (Guillaume et al., 2016a, 2016b), water shortage and pollution (Merten et al., 2016; Röll et al., 2019) and biodiversity loss (Koh and Wilcove, 2008). Intensive farming systems of oil palm rely on fertilizer application to sustain high

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yields, leading to high nutrient surplus. Frequent herbicide applications are used to maintain bare soils to facilitate field operations and limit resource competition between palms and understory vegetation (Luke et al., 2020). As a consequence, soils experience high erosion (Guillaume et al., 2015) and nutrient accumulation (Quezada et al., 2019) that reduce soil organic matter (SOM) and impair soil biological processes sustained by SOM (Rüegg et al., 2019). The degradation of natural soil functions causes intensive oil palm farming systems to be increasingly dependent on synthetic agricultural inputs (Bender et al., 2016).

Several practices have been adopted in industrial plantations to limit soil degradation. The introduction of legume cover crops in the understory limits soil erosion, suppresses weeds, and provides nitrogen (N) (Samedani et al., 2015). The return of fresh or composted organic residues (empty fruit bunches, kernel shells, press fibres, mill effluent) to the plantation is a source of organic amendments (Bessou et al., 2017). An improved management of oil palm fronds such as mulching can foster soil microbial activity (Rüegg et al., 2019). Biodiversity can be favored by the creation of tree islands in the plantation (Teuscher et al., 2016). While these practices have demonstrated the potential to improve environmental performance in oil palm plantations (Luke et al., 2020), they are rarely applied to the entire surface of the plantation owing to the limited availability of organic residues (Quezada et al., 2022). Smallholders face additional barriers due to the labour requirements of cover crop management and the financial costs of seed and transportation of residues.

In parallel to the high-input industrial model that is also largely followed by smallholders around the tropics, low-input subsistence-based models of oil palm cultivation are implemented in South-Est Asia and Africa by independent smallholders who have few interactions with local agro-industries and limited financial resources (Iyabano et al., 2014; Moulin et al., 2017). In Cameroon, most independent smallholders cannot afford to buy fertilizers or phytosanitary products (Iyabano et al., 2014). These farming systems typically lack any synthetic agricultural inputs, and rely on the initial nutrient input from burning forest biomass (Gay-des-Combes et al., 2017). In addition, oil palms are intercropped with food or cash crops (*e.g.,* plantain banana) to ensure a return on investment in the first years of the plantation, and to reduce weeding costs (Nchanji et al., 2016). Besides local smallholders' plantations (SH), oil palm production is promoted in Cameroon by investments from local or urban elites. Elites' plantations (EL) are usually larger (from 5 to several hundred hectares), fertilized and with a more thoroughly conducted field operation (Iyabano et al., 2014). Palm oil production in SH plantations can be as low as 2 Mg fresh fruit bunches (FFB) ha^{-1} yr^{-1} or < 1 Mg crude palm oil (CPO) ha^{-1} yr^{-1} (Nkongho et al., 2014), but it can sometimes approach the productivity of industrial plantations (14–16 Mg FFB ha^{-1} yr^{-1}) in the most productive EL plantations (Rafflegeau et al., 2010). The yield disparity may be partly explained by the low N and potassium (K) nutrition indices observed in the non-industrial plantations in Cameroon and Indonesia (Rafflegeau et al., 2010; Woittiez et al., 2019). Despite lower yield, the return to land (economic margin per hectare) may reach a similar level in both SH et EL farming systems (Iyabano et al., 2014). On this basis, it can be hypothesized that the extensive low-input farming system of SH limits the environmental impacts of oil palm plantations, thus increasing its sustainability. Unfortunately, only scarce data related to extensive oil palm farming systems are available in the literature to confirm this hypothesis.

Using oil palm plantations in Cameroon, this study aimed to assess the sustainability of the SH model as a no-input subsistence-based oil palm farming system, and using EL plantations as a benchmark for plantations with similar management, but using agricultural inputs. The specific objectives were to: i) assess the dynamics of SOC and available nutrients after forest conversion to oil palm plantation over one cultivation cycle (30 years), ii) determine changes in nutrient deficiencies with cultivation duration and iii) quantify oil palm productivity.

2. Materials and methods

2.1. Study region

The study was conducted in the municipality of Ngwei, located between Yaoundé and Douala, in the Sanaga Maritime Division of Cameroon (03°35′- 03°48′ N, 10°10′- 10°17′ E). The municipality covers 848 km^2. It experiences a wet tropical climate (2460 mm, 26 °C) with a monomodal rainfall regime including a dry season between December and February, with the highest rainfall in July and August. The region is flat to slightly hilly (30–300 m a.s.l) and dominated by Ferralsols. The local rainforest is composed of a mixture of evergreen tree species (e.g. *Irvingia gabonensis*, *Monodora mysristica*, *Strombosopsis tetrandra*, *Symphonia globulifera*) and deciduous tree species such as *Baillonella toxisperma*, *Milicia excelsa, Guibourtia demeusei*, *Albzia* ssp., *Spathodea campanulata*, *Pterocarpus soyauxii*, *Cylicodiscus gabonensis*. The oil palm (*Elaeis guineensis*) is native from the region, and thus has suitable pedoclimatic conditions for its growth.

The Ngwei municipality encompasses 29 villages with a total population of 15′000 inhabitants. Oil palm plantations cover 5′000 ha of the municipality (Mesmin et al., 2021). Most plantations (about 80%) are smallholders with less than 5 ha, though they represent less than 20% of the total surface area. Plantations managed by elite can reach up to 300 ha (Tchindjang, 2017). Smallholders and elite oil palm farmers extend their plantations progressively, depending on their financial situation, but smallholders do it less frequently and on smaller areas (<1 ha) at a time (Tchindjang, 2017).

2.2. Plantations selection and characteristics

Oil palm plantations in the Ngwei region were selected to ensure a homogeneity between plantations in terms of pedological condition, *i.e.,* deep well-drained Ferralsol on flat areas, and land-use trajectory, *i.e.,* directly established after forest clearance and with intercropping in the juvenile phase before the fifth year. In total, nine farms having a chronosequence of plantation age were selected for a total of 42 fields with age ranging from 2- to 29-year-old (Fig. 1).

To establish plantations, big trees are logged and left on site if their wood does not represent a substantial value. The rest of the vegetation is slashed and burnt to clear the land, with nutrient becoming integrated into the soil from ashes and decomposing wood not fully burnt. All fields were intercropped during the juvenile phase with food crops such as

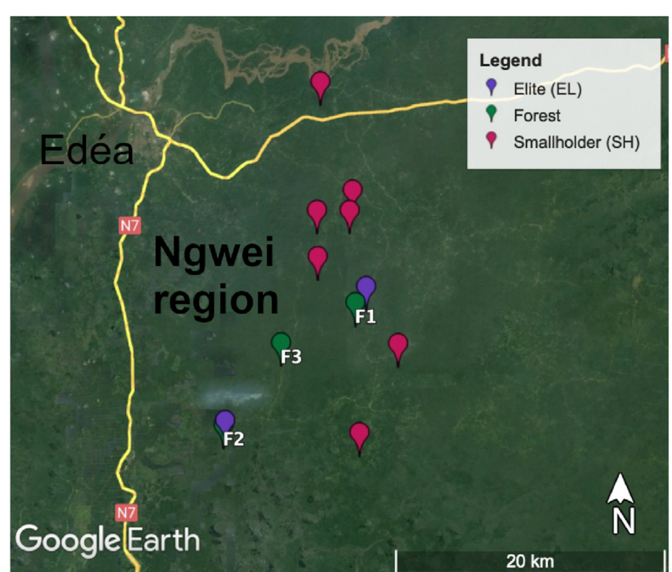

Fig. 1. Map of the study region with the selected plantations and forest sites.

plantains banana (*Musa* ssp.), maize (*Zea mays*), egusi (*Cucumeropsis mannii*), and macabo (*Xanthosoma mafaffa*). Plantain is planted in between palms, about 4 m away from the palm saplings, whereas the other crops can be sown as close as to 1 m from the young palm. Intercropping stops when the competition with palm roots and for light becomes too strong, *i.e.* about 5 years for plantain, which last the longest. It is also common to cultivate food crops, *e.g.* groundnut (*Arachis hypogaea*), for 1–2 years after forest clearing and before establishing oil palm seedling, though we avoided selecting such cropped sites to ensure a homogeneity in terms of land-use trajectory. The typical distance between palms is 8 m (160 palms ha^{-1}) but can vary between 7.5 and 9 m (Table 1). The oil palm variety is generally *Tenera* (hybrid of *Dura* and *Pisifera*) obtained from IRAD, but some farmers have also planted material obtained at local industrial plantations (SOCAPALM, CDC) (Table 1). Out of the nine farms, two used chemical inputs in the form of mineral fertilizers and herbicides, and were therefore classified as elite plantations (EL), whereas the seven other farms did not use any agronomic inputs and were classified as smallholder plantations (SH) following the classification of Nkongho et al. (2015). In EL, fertilizers are applied around the palm at a rate of 200g of urea, 500g of KCl and 200g of Kieserite ($MgSO_4$) per palm per year during juvenile phase. During the production phase (after 4–5 years), 50g of urea, 2000 g of KCl and 1000 g of kieserite per palm are applied yearly. Fertilization occurs at the end of the wet season (October–November) before the main harvesting season, but some EL farmers apply half of the fertilisers in April–May before the small harvesting season, and half in October–November. The typical plantation maintenance consists in pruning the palm trees and weeding mechanically twice a year (July and January). A third mechanical or chemical (with glyphosate, only in EL) weeding may occur in both plantation types. SH plantations are not necessarily characterized by less pruning and weeding, but some of them experience very low maintenance frequency (less than once a year) (Table 1). In addition to oil palm plantations, three mature forest sites with similar soil characteristics were selected in the region close to the plantations, as reference for soil properties (Fig. 1).

2.3. Study design and data collection

Soil sampling occurred in early 2019 (January–February), corresponding to the main production season. A total of 42 fields with different age category were selected in the nine plantations. In each field, a plot encompassing 25 palms (ca 50 × 50 m^2) was established in a homogenous and representative zone of the field. Zones with missing or unhealthy palms were avoided to represent the optimum production condition in the selected field. In each plot, five out of the 25 palms were randomly selected to conduct plant and soil measurements. Soil samples (0–10 cm) were collected in the interrow, 4 m away from each of the five palms and pooled to make one mixed sample per plot. Interrows represent about 80% of the surface area in the plantations, the rest being the weeded circles and the frond piles. A bi-partite root auger (Eijkelkamp®) of 8 cm diameter was used to collect soil samples, which enables to determine the collected volume and thus, soil bulk density.

Oil palm productivity was estimated using the standing fruit bunches methodology (Ochs and Quencez, 1982). As fruit bunches need 6 months to develop, counting the number of inflorescences and bunches twice a year allows us to determine the number of fruit bunches produced per tree over the year. By measuring the average fresh fruit bunch (FFB) weight, it is then possible to determine the potential annual production in the plot by multiplying this average value by the number of FFB produced, assuming that all FFB reach full maturity and are harvested without losses. Fruit bunches and inflorescences were counted on each of the five palms per plot during the soil sampling campaign, and again in June–July 2019 during the second productive season (small season). At the time of the first monitoring, the frond holding the newest inflorescence was marked to avoid double counting. At each field campaign, the weight of all available mature FFB from the 5 selected palms was measured directly in the field. For each plot, a minimum of 5 FFB was measured to calculate the average fresh weight of the FFB in the respective plot.

During the second field campaign, the height of the five selected oil palms was measured, using a clinometer (Suunto®) in mature plantation. At the same time, leaflet samples were collected for foliar analysis. The methodology corresponded to the recommendation of the IRAD, which consists in collecting leaflets in each plot, respectively on five oil palms, along both sides of the 17th palm frond to obtain a mixed plant sample representative of the frond's leaflets.

Table 1
Characteristics of the selected smallholder and elite plantations.

Characteristics	Smallholder	Elite
Origin	Forest	Forest
Plantation size	<5 ha	>5 ha
Interrow	8–9 m	7.5–9 m
Seedling producer	IRAD/SOCAPALM/CDC	IRAD
Intercropping	yes	yes
Fertilization	no	yes
Weeding and pruning	<1–3 times per year	2-3 times per year
Weeding type	Mechanical	Mechanical/chemical

2.4. Laboratory analysis

Fresh soil samples were kept in plastic bags until weighing in the laboratory at Youndé I University. Directly after weighing, soils were sieved at 2 mm and a sub-sample (10 g) of fresh sieved soil (<2 mm) was dried at 105 °C to determine the dry mass of fine soil used to calculate bulk density. Because of the absence of stones and the negligeable weight of organic material larger than 2 mm, the volume of soil collected with the auger was not corrected before calculating the bulk density. The rest of the sieved soil was dried at 40 °C.

Laboratory analyses were conducted in the Laboratory of Ecological Systems at EPFL, the Swiss Federal Institute of Technology in Lausanne, Switzerland. Soil particle size analysis followed the pipette method after destruction of organic matter with 30% H_2O_2. Soil pH was determined in a 1:2.5 soil-to-water ratio after equilibrating for 2 h. Soil organic carbon (SOC) and total nitrogen contents were measured on ground soil samples using an elemental analyzer (Eurovector®). Exchangeable cations (Ca, Mg and K) were extracted with Mehlich-3 solution (Mehlich, 1984) and analyzed with ICP-MS (PerkinElmer®). Available soil phosphorus (P) was extracted following Bray II methodology (Bray and Kurtz, 1945) and the concentration of P in the extract was determined colorimetrically with a UV/VIS spectrometer (Lambda 35, PerkinElmer®).

Leave samples were ground and analyzed for total C and N content using an elemental analyzer (Eurovector®). To determine leaflet nutrients contents (K, Mg, Ca and P), 500 mg of ground samples were mineralized with 2 ml H_2O milli-Q®, 2 ml H_2O_2 30% suprapur® and 6 ml HNO_3 65% suprapur® in a microwave. The heating program was set to reach 100 °C in 10 min (maintained for 5 min) followed by 10 min to reach 230 °C (maintained for 20 min) before a decrease of temperature during 27 min to reach 70 °C. The solution was analyzed with ICP-MS (PerkinElmer®).

2.5. Clay content correction

As clay tended to be higher in the oldest plantations (Fig. S1), soil organic carbon stocks were corrected for fixed clay content corresponding to the clay content in forests plots (22%) (Fig. S1) assuming linear relationship between clay and SOC contents in similar conditions (Guillaume et al., 2022):

$$Cs = Cl_F \times BD_S \times \frac{SOC_S}{Cl_S} \times D \times 0.1 \quad \text{[Eq. 1]}$$

where *Cs* is the SOC stocks (kg m^{-2}) in the sampled plot, Cl_F (%) the average clay content in forest plots, BD_S the bulk density in the sampled plot, SOC_S the SOC content (%) in the sampled plot, Cl_S the clay content (%) in the sampled plot, *D* the sampling depth (cm) and *0.1* a factor to obtain the chosen unit.

2.6. Nutrition indices

Nutrient deficiencies were estimated using nitrogen nutrition index (NNI) and potassium nutrition index (KNI) calculated with the parameters of the equations given by Rafflegeau et al. (2010). Assuming no nutrient deficiencies in industrial plantations, a regional model of critical N (Nc) and K (Kc) contents in leaflets (i.e., the nutrient concentration lower limits at which no deficiency occurs) was constructed by Rafflegeau et al. (2010) using data from three oil palm compagnies in the same region (Edéa region) as our study. The model for Nc was:

$$Nc = 28924 - 0.0109n - 0.0007n^2 \quad \text{[Eq. 2]}$$

where *Nc* is the nitrogen critical level (% DM), *n* is the age of the plantation (years).

For Kc the model from 3 to 8 years was:

$$Kc = -0.03n + 1.19 \quad \text{[Eq. 3]}$$

and from 9 years onwards:

$$Kc = 0.95 \quad \text{[Eq. 4]}$$

where *Kc* is the potassium critical level (% DM), *n* is the age of the plantation (years). Nutrition indices were calculated as the ratio between the N or K contents in leaflets and the respective critical content.

2.7. Statistics

All statistical analyses were performed using R software 4.2.2 (R Core Team, 2022). Effects of farming system and age on soil and plant variables were tested by ANCOVA models (function *lm*). If only one factor was significant (age or farming system), the other was removed and data were analyzed with a linear regression model for the age (function *lm*) or with an ANOVA model for the system (function *aov*). If the interaction between factors was significant, both farming systems were analyzed separately by linear regression. If data appeared not to be linear, segmented regression models were fitted (function *segments* in *segmented* package). Segmented regressions were selected only if breaking point was significant. Normality and homoscedasticity assumptions were tested by Shapiro-Wilk (function *shapiro.test*) and Bartlett (function *Bartlett.test*) tests, respectively. If data were not meeting the assumptions, a Monte Carlo simulation with 10,000 replicates was performed (function *PermTest* in *pgirmess* package) on the model. If not specified, data are presented as mean ± standard error (SE) and discussed differences are significant at least at p-value <0.05.

3. Results

3.1. Dynamics of SOC and nutrients

Soil organic carbon stocks in the topsoil (0–10 cm) of smallholder (SH) and elite plantations (EL) decreased by −0.029 ± 0.012 kg C m^{-2} yr^{-1} after the forest conversion to oil palm plantations, but no effect of the farming system (p-value >0.98) and no interaction between the system and the age (p-value >0.16) were observed on SOC losses (Fig. 2). Forest sites had a SOC:clay ratio of 0.110 that decreased by 0.0015 ± 0.0005 per year, *i.e.,* losing 41 ± 14% in 30 years.

A significant interaction (p-value <0.02) was observed between age and farming system on C:N ratios. While C:N ratios were not affected by age in SH (p-value >0.25), it increased by 0.10 ± 0.03 yr^{-1} in EL, indicating higher N than C losses in this system (Fig. 2b). Soil pH and bulk density were not affected by the forest conversion to any oil palm farming system (p-values >0.16) with mean and SD of 4.5 ± 0.4 and 1.37 ± 0.1 g cm^{-3} in plantations, respectively and of 4.3 ± 0.2 and 1.35 ± 0.1 g cm^{-3} in forests, respectively.

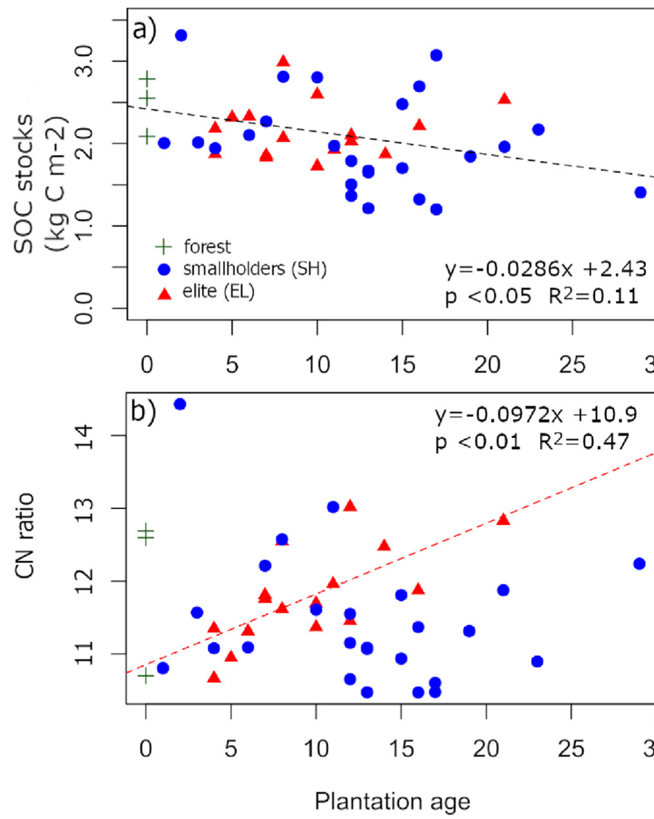

Fig. 2. Effect of forest conversion to oil palm plantations on a) soil organic carbon (SOC) and b) C:N ratio, depending on age and farming system. Dashed lines represent in a) the effect of age regardless of farming system as it had no effect on SOC, and in b) the effect of age on C:N ratio only in elite plantations as the effect in smallholder plantations was not significant.

Potassium decreased linearly after forest conversion by -0.009 ± 0.002 cmol + kg soil^{-1} yr^{-1} until stabilizing after 7.3 ± 0.9 years around 0.04 cmol + kg soil^{-1} (Fig. 3a). By contrast to other nutrients, available P was not affected by age (p-value = 0.15) but by farming system. Phosphorous levels were similar in SH and in forest, but available P was depleted in EL as compared to forests (confidence interval (CI): −3.2; −0.5) et SH (CI: −1.9; −0.5). When EL was considered separately, available P decreased by −0.35 ± 0.14 mg P kg soil^{-1} yr^{-1} until 5.0 ± 2.1 years and then stabilized around 1.5 mg P kg soil^{-1}, *i.e.,* half of forest content (Fig. 3b).

After an increase following forest conversion, exchangeable Ca decreased with age (p-value <0.01) with no difference among farming systems. Data were log-transformed to reach normality, indicating a high variability at young age (Fig. 3c). Magnesium followed similar dynamic as K but stabilized later (14.3 ± 2.7 years) around 0.2 cmol+ kg soil^{-1} (Fig. 3d) and, similarly to Ca, several plantations had more exchangeable Mg as compared to forest.

3.2. Plant nutrient contents and biomass productivity

Leaflet N content decreased by −0.016 ± 0.007% of DM yr^{-1} regardless of the farming system (p-value >0.70) (Fig. 4b). Nonetheless, the model R^2 was low (0.15), indicating that other factors than age had greater effects on N content. The NNI remained low in all plots (0.65 ±

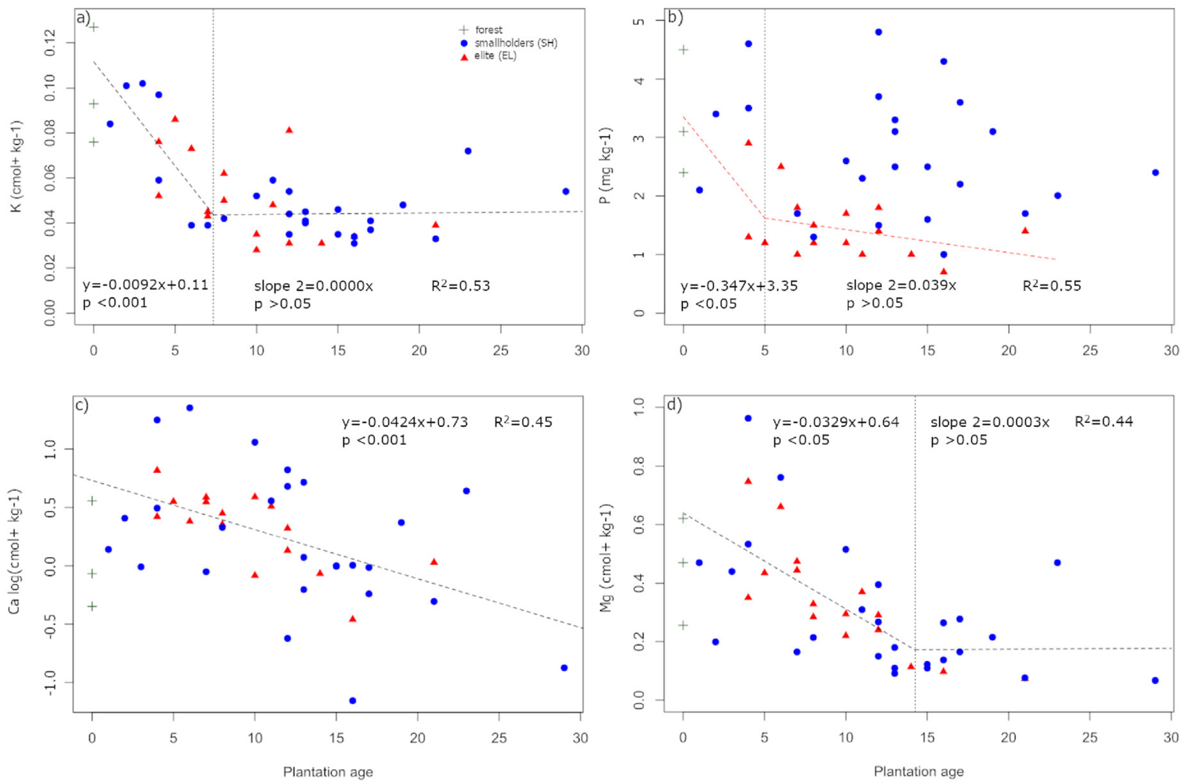

Fig. 3. Available nutrient content in the topsoil (0–10 cm) depending on farming system and age for available K (a), P (b), Ca (c) and Mg (d). Dashed lines represent the regression or segmented regression between nutrient content and age, regardless of the farming system when this factor was not significant (a, c and d) or only in elite plantations when an interaction between factors occurred (b). Vertical dotted line represents the breaking point of the segmented regression.

SD: 0.07) and was not affected by the age (p-value >0.50) nor by the farming system (p-value >0.65). Leaflets K content was influenced by age differently in both systems (Fig. 4a). Potassium content was higher in young EL but decreased by -0.024 ± 0.007% DM yr^{-1} to reach similar levels as in SH in older plantations, while K levels in SH remained at a similarly low level (p-values > 0.46). Similarly, the KNI decreased with age (-0.02 yr^{-1}) in EL, but remained low and variable ($0.68 \pm$ SD: 0.13) in SH. At younger stage, the KNI in EL was close to optimal (intercept: 1.03). Leaflets Mg content was not affected by the system (p-value >0.50) but increased by 0.008 ± 0.003% DM yr^{-1} with palm age. Leaflets Ca (mean: 1.44%, SD: 0.20%, p-value >0.11) and P (mean: 0.027%, SD: 0.0027%, p-value >0.23) were not affected by age nor by the system (not shown).

Palm growth was similar in SH and EL plantations (p-value > 0.26) and increased linearly at a rate of 0.46 ± 0.03 m yr^{-1} (Fig. 5a). By contrast, palm productivity was not affected by age but was lower in SH, with an average wet weight of standing fresh fruit bunches (FFB) of 59 ± 12 kg per palm lower in SH (156 ± 9 kg palm^{-1}) than in EL (215 ± 7 kg palm^{-1}) (Fig. 5b). The variability among SH plantations was important with FFB production varying from 55 to 232 kg palm^{-1}, whereas it was less than 100 kg palm^{-1} in EL plantations (164–256 kg palm^{-1}). The lower productivity resulted from a lower number of standing FFB on SH (7.9 ± 0.4) as compared to EL palms (11.3 ± 0.4) and not because of lighter FFB (mean: 19.5, SD: 2.1, p-value > 0.27).

4. Discussion

4.1. Soil degradation

Soil C losses are commonly observed after the establishment of oil palm plantations (Chiti et al., 2014; Guillaume et al., 2015). The rate of SOC losses (0.029 kg C m^{-2} yr^{-1}) were, for the same soil layers, 70% lower than that reported after rainforest conversion in Indonesia, and 35% lower than after pasture conversion in Colombia (Guillaume et al., 2018; Quezada et al., 2019). As SOC losses depend strongly on initial SOC stocks (Guillaume et al., 2021), it is difficult to link differences in losses to management practices. Nonetheless, the strong SOC losses in Indonesia were associated to soil erosion (Guillaume et al., 2015). Thus, the high soil coverage resulting from a less intensive weeding in Cameroonian smallholder plantations may have limited soil erosion and favored soil C input from understory plants. The correction of SOC stocks to the clay content of the forest sites yielded lower rate of SOC losses than that estimated without correction (0.048 kg C m^{-2} yr^{-1}) and non-corrected SOC stocks were higher in plantations older than 17 year (Fig. S1). A partial recovery of SOC stocks was observed in plantations in Colombia and this SOC dynamics was explained by a higher accumulation of oil palm-derived C during the latter phase of plantation than the decomposition of former SOC, which occurred mainly during the early phase after conversion (Quezada et al., 2019). Hence, the higher SOC stocks in the oldest plantations may not only result from a bias due to differences in clay content, but may be a direct consequence of plantation ageing that can intervene in certain circumstances. The oldest smallholder plantations in Cameroon are often less intensively managed, exhibit a denser understory vegetation, and have higher oil palm root density (Rüegg et al., 2019). This calls for further research to investigate the potential of SOC stock recovery in old or abandoned plantations.

The nutrient availability in SH and EL plantations showed completely different dynamics than in industrial plantations (Fig. 3). By contrast to the long lasting accumulation of nutrient observed in all management zones of industrial plantations (Quezada et al., 2019, 2022), the investigated farming systems led to a nutrient depletion, even in the EL farming system were nutrients were applied (Fig. 3). Young plantations showed similar or higher levels of Ca and Mg than forest sites, which can be explained by the initial nutrient input from the slash-and-burn practice (Fig. 3c and d). The initial nutrient input, however, did not lead to a peak of available K and P in young plantations as they remained at similar

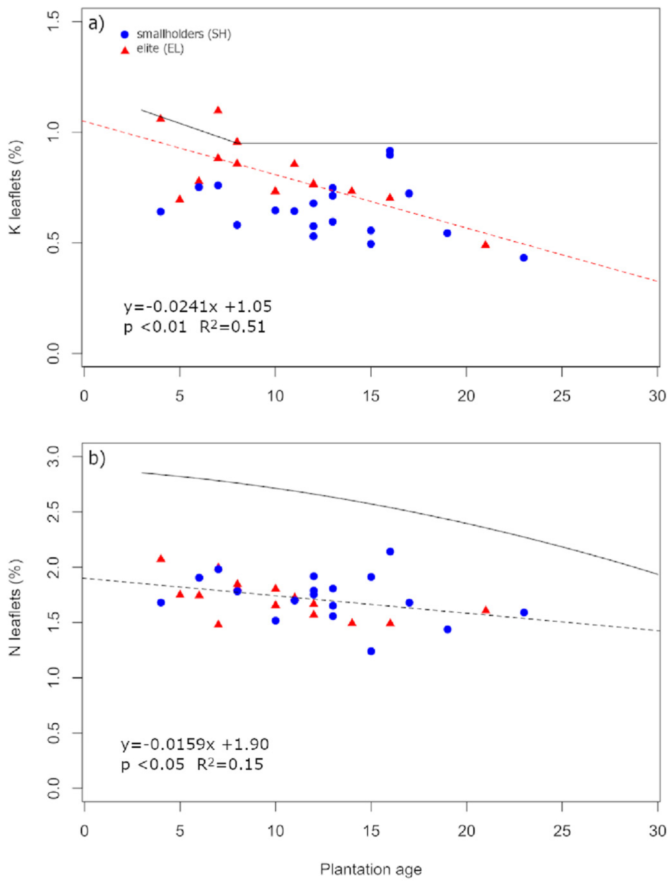

Fig. 4. Oil palm leaflets contents of a) K and b) N in function of plantation age and farming system. Solid lines represent the critical K and N contents in function of age, estimated by Rafflegeau et al. (2010) from industrial plantations in the study region. Dashed lines represent the effect of age regardless of the farming system (b) or only in elite plantations (a).

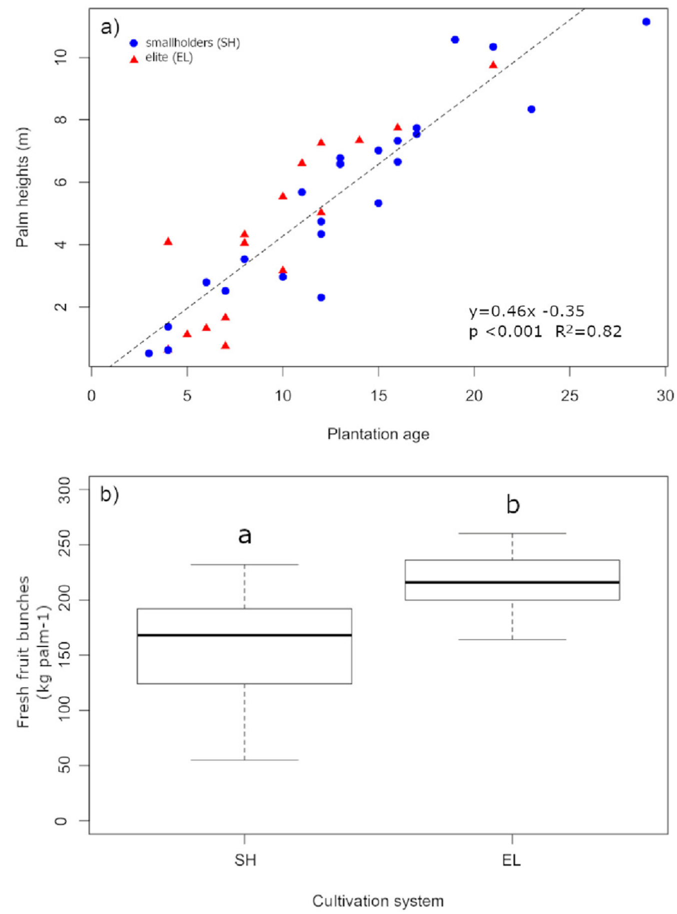

Fig. 5. Effect of farming system on biomass productivity indicated by (a) palm height and (b) fresh fruit bunches (FFB) weight per palm. Dashed lines in (a) represent the effect of age regardless of the farming system. Lowercase letters in b) represent significant difference between boxplots.

levels than in forest (Fig. 3a and b). While the P input from ashes is much lower than the K input (Giardina et al., 2000), the absence of K accumulation may result from its absorption by the intercrops in the first years of the plantation. Tuber crops, due to high K export, are expected to have a more negative impact on K availability (Rafflegeau et al., 2010). Nonetheless, the effects of food intercropping on nutrient deficiency and oil palm yield have rarely been documented, though reported to be non-significant by Okyere et al. (2014), and its economic benefit for smallholders is clear (Nchanji et al., 2016).

4.2. Nutrient deficiencies and production

The comparison of leaflet N and K contents with references to industrial plantations indicates strong nutrient deficiencies in both SH and EL systems, as previously reported in smallholder plantations in Cameroon and Indonesia (Rafflegeau et al., 2010; Woittiez et al., 2019). Potassium deficiencies are common in oil palm production because as much as 160 kg ha^{-1} yr^{-1} of K is exported in high yielding plantations (Cui et al., 2021). While K deficiency occurred at all development stages in the SH system, K fertilization in EL system limited K deficiency during the immature phase (Fig. 4). During the production phase, however, the fertilization was not sufficient as K deficiency increased to reach the level observed in SH system. Nitrogen deficiencies were similar in both farming systems but, by contrast to Rafflegeau et al. (2010), were stronger than K deficiencies. While the range of leaflet K content (0.5–1% DM) was similar to the range observed in smallholder plantations in Cameroon and in Indonesia, the range of N content was about 0.5% lower (Rafflegeau et al., 2010; Woittiez et al., 2019). This might result from the very low N fertilization rate (23 g N palm^{-1} in production phase), but a systematic analytical bias cannot be excluded as N content, and thus the Nc content reference, may be affected by the method of measurement (e.g. Kjeldahl method *vs.* elemental analyzer).

Oil palm growth was similar in both farming systems and the rate was comparable (0.46 *vs.* 0.48 m yr^{-1}) to the one observed in industrial plantations in Malaysia (Tan et al., 2014). This suggests that nutrient deficiencies had no effect on oil palm growth and thus, aboveground biomass productivity, but only on FFB production. The FFB weight was in the upper range of weights observed in plantations with similar characteristics and fertilizer application in Ghana (Okyere et al., 2014), but it was slightly lower than the one observed in an industrial plantation in Indonesia, with higher fertilization (19 vs. 23 kg FFB^{-1}) (Darras et al., 2019). As the number of FFB per palms in EL (11 palms^{-1}) was similar to the one observed in the industrial plantation, this suggests that EL farming system in Cameroon may approach the performance of industrial plantations despite lower fertilization (3.6 kg N, 148 kg K, and 31 kg Mg ha^{-1} yr^{-1} vs. 260 kg N, 220 kg K, and 50 kg P ha^{-1} yr^{-1}). By contrast, the absence of fertilization in SH did not reduce the average weight of FFB (19 kg), but decreased the number of FFB per palms to 7.9.

4.3. Sustainability of the farming systems

The production in SH and EL farming systems seems jeopardized by the nutrient depletion induced in the agroecosystem. The fertilization in EL was sufficient to promote oil palm production by 38 ± 11%, but was not sufficient to maintain nutrient stocks in the soil. This indicates that production in both SH and EL is supported by nutrient supply from the soil. Additionally, the enhanced biomass export due to fertilization seems to have induced soil N and P depletion in EL, two nutrients that were not brought by fertilizers for (P) or at a very low rate (N, with urea), whereas this depletion is not observed in SH plantation (Fig. 3b). While N decreased in both systems because of soil organic matter losses (SOM), N decreased faster than C in EL, as indicated by the increase of the C:N ratio in EL system only (Fig. 2b). This suggests N mining in SOM by soil microorganisms due to low N availability (Cui et al., 2020). Soil P depletion was not expressed as lower leaflet P content yet, but this might be a future risk for production if P stocks continue to decrease. A similar risk is plausible for micro-nutrients such as boron, copper, or zinc as they are not applied as fertilizer despite high biomass export (Woittiez et al., 2017). Overall, the results show that the initial nutrient inputs from forest biomass burning is insufficient to sustain oil palm production over even one plantation cycle. Hence, nutrient export in FFB is supported by soil nutrient supply, leading to soil nutrient depletion, even at the current fertilization rates in EL plantations.

Smallholder and elite farming systems bring economic benefits to thousands of Cameroonian farmers (Iyabano et al., 2014; Nchanji et al., 2016; Nkongho et al., 2015), but these no-input (SH) or low-input (EL) farming systems do not qualify for low-input sustainable agriculture (Biala et al., 2007; Sarkar et al., 2020) as they do not safeguard natural resources in the long run. Nonetheless, they showed encouraging features that could be reinforced by appropriate practices. First, moderate fertilization, as compared to industrial practices, is able to induce high gains in yield. Second, SOC losses seem limited even though no specific management practices were specifically implemented for that purpose. Thirdly, intercropping brings economic benefits and spares forested land that would have been otherwise converted for food production. Finally, the low but frequent presence of forest trees within the plantation (spared for non-timber product exploitation) and the high richness and abundance of herbaceous, fern and bush species due to less intensive weeding, may facilitate land restoration after oil palm cultivation. In this respect, these Cameroonian farming systems can serve as a laboratory to study agroecological practices in oil palm production.

The potential optimization of the two farming systems illustrate the two ways of sustainable intensification as proposed by Struik and Kuyper (2017), *i.e.* 1) a targeted intensification for EL farming systems to compensate for nutrient export in the harvest and 2) a further de-intensification in SH farming systems to limit soil nutrient depletion. In EL, NPK and micronutrients fertilization should compensate for nutrient export to ensure the sustainability of the production over several plantation cycles (Quezada et al., 2019). This should further have a positive impact on yield. Nonetheless, it seems not necessary to reach the fertilization levels of industrial plantations as fertilization trials suggest that high yield can be reached at lower fertilization rates (Darras et al., 2019). In parallel, conservation practices, especially to limit SOC losses, should be implemented or reinforced (Quezada et al., 2022).

This intensification pathway is not an option for subsistence-based models with little access to synthetic agricultural inputs. For SH farming system, the industrial model with high palm density is not a sustainable option, because of nutrient export. Lower palm densities coupled with nitrogen-fixing crops, or crops that have little nutrient demand (e.g., legume cover or cash crops), and the recycling of biomass residues (Bessou et al., 2017; Luke et al., 2020), might be better suited to no-input oil palm farming system practices. Incorporating non-timber forest products (*e.g. Garcinia kola*, *Garcinia lucida*, *Mammea Africana*, *Irvingia gabonensis*, *Dacryodes macrophylla*, *Ricinodendron heudelotii* var. *Africanum*), which are already a significant source of revenue in Cameroon (Awono et al., 2016), might also offer interesting options to limit nutrient requirement, while maximizing economic return on land.

5. Conclusions

Two non-industrial oil palm farming systems differing mainly by the application (EL system) or not (SH) of fertiliser were compared to assess if they could offer environmentally-friendly alternatives to intensive oil palm farming systems. The nutrient deficiency observed in both systems induce a yield gap, but did not prevent farmers from making a profit. While this may be enough for a subsistence-based models from a producer perspective, the sustainability of these two systems is not ensured over several oil palm cycles due the gradual nutrient depletion. The optimization of the two systems would require a detailed nutrient budget to fine tune the fertilization in EL systems to reduce the yield gap, and to adapt the oil palm density in SH system to limit the nutrient export. Moreover, an accounting of potential nutrient sources other than synthetic fertilizer should be performed in the local urban- and agro-ecosystems. Nutrient inputs from palm oil value-chain, but also from other regional agronomical and economic activities, may be low-cost sources of nutrient to compensate for the export in a subsistence-based farming system.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.farsys.2023.100006.

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