Long-term crop residue application increases oil palm yield and maintains temporal stability of production

Hsiao-Hang Tao[1*], Jake L. Snaddon[2], Eleanor M. Slade[1,3], Jean-Pierre Caliman[4], Rudi H. Widodo[4], Suhardi[4], Kathrine J. Willis[1, 5, 6]

1 Department of Zoology, University of Oxford, Oxford, Oxfordshire, United Kingdom

2 Centre for Biological Sciences, University of Southampton, Southampton, United Kingdom

3 Lancaster Environment Centre, Lancaster University, Lancaster, Lancashire, United Kingdom

4 SMART Research Institute, Pt SMART, Pekanbaru, Riau, Indonesia

5 Royal Botanical Gardens, Kew, Richmond, Surrey, United Kingdom

6 Department of Biology, University of Bergen, Bergen, Norway

* Correspondence to: Hsiao-Hang Tao, hsiaohang.tao@gmail.com

ABSTRACT

Crop residue management is an important agricultural practice that has a high potential to improve soil health and optimize crop production. Compared to annual crops, relatively little is known about crop residue management effects on the yield and temporal stability of perennial crop production. Oil palm is an economically important tropical crop, which development has been reported to contribute to severe soil degradation. The use of crop residue application has been shown to enhance soil quality and soil ecosystem functions of oil palm cultivation. However, this management technique is not widely implemented mainly due to the uncertainty of the yield responses, compared to the conventional practice of using solely chemical fertilizers as nutrient inputs. This study aims to understand the effects of crop residue application on oil palm yield and temporal stability of production. We examined a major oil palm residue, the empty fruit bunch (EFB), which has been shown to mitigate soil degradation by increasing soil fertility and soil biological activities; however, its effects on crop yield remain unclear. We compared 15 years of crop yield performance from a field trial of continuous EFB application of three application rates, and a reference treatment of conventional chemical fertilizers with no addition of EFB, from an oil palm plantation in Sumatra, Indonesia. Results show that EFB application either maintained or increased crop yield, compared to the reference treatment. Specifically, the medium application rate of EFB treatment (60 t ha^{-1} yr^{-1}) resulted in higher cumulative and annual crop yield than the reference treatment, and the increase was positively associated with soil organic carbon. Yield stability over 15 years was similar under EFB of three application rates and the reference treatment, while increases in relative humidity positively influenced crop yield with a lag effect of two years. These findings will inform the design of optimal EFB application schemes that enhance sustainable intensification of oil palm cultivation.

KEYWORDS

Elaeis guineensis, crop residue, yield stability, empty fruit bunch, perennial crop, soil organic carbon, chemical fertilizer, sustainable oil palm, relative humidity, Indonesia.

1. INTRODUCTION

Optimizing agricultural management practices to enhance ecosystem health and maintain high crop yield is important for the sustainable development of agriculture (Garnett et al., 2013). Crop residue application is a widely used management practice which can benefit soil fertility and ecosystem functioning by providing trophic resources to the soil, modifying the soil abiotic environment, and enhancing soil biological activities (Edmeades, 2003). Optimizing crop residue management is especially important for oil palm (*Elaeis guineensis*), an economically important tropical crop which produces vegetable oil widely used in the production of food and detergents, and as a feedstock for biofuel. The land area under oil palm cultivation has reached 16.4 million ha globally in 2014, equivalent to 10% of the world's permanent croplands (FAO, 2015; Kurnia et al., 2016). More than half of the world's plantations are located in Malaysia and Indonesia; these two countries produced 85% of the 56 million tons of crude palm oil produced worldwide in 2013 (FAO, 2015). The cultivation of oil palm can lead to soil degradation, through the removal of understory vegetation, intensive use of chemical fertilizers, and the lack of carbon returns from crop residues (Guillaume et al., 2015). In the past decade, the practice of applying oil palm residues with reduced chemical fertilizers has increased within oil palm plantations, to replace the conventional practice using chemical fertilizers as the sole nutrient inputs (Singh et al., 2010). Crop residue application in oil palm has been shown to positively influence soil quality and soil ecosystem functions (Comte et al., 2013; Tao et al., 2016). However, the effects of crop residue application on oil palm yield remain unclear (Abu Bakar et al., 2010; Chiew and Rahman, 2002). The uncertainty of yield responses under crop residue application, and the lack of identification of optimal application schemes remain obstacles for the informed use of this practice (Fairhurst and Griffiths, 2014).

The effects of crop residue addition on crop production are highly associated with climatic conditions and soil characteristics (Edmeades, 2003; Rusinamhodzi et al., 2011). Crop residue application influences crop yield through different mechanisms; one of which is through increasing soil organic carbon (Lal, 2010). Climatic factors can affect the decomposition rate of crop residues, which in terms influence soil organic carbon and crop yield (Rusinamhodzi et al., 2011; Ventrella et al., 2016). The potential temporal fluctuations in crop residue decomposition can therefore result in pronounced temporal variations in available soil nutrients, soil carbon, and thus crop production. In comparison, chemical fertilizers may serve as a more stable and readily available mineral nutrient source, contributing to a more stabilized crop yield over time. When the cumulative crop productivity is similar, farms with higher temporal stability in yield are likely to have better operations and economic returns (Fairhurst and Griffiths, 2014). In addition to the effects of management practices, climatic conditions such as radiation and water supply, can directly influence crop yield, and these effects may override the effects of management practices (Rusinamhodzi et al., 2011). However, the majority of current studies have focused on the net changes in annual crop yield under crop residue addition, and relatively little information is available on temporal changes in perennial crop yield under crop residue management, especially in tropical regions (Edmeades, 2003).

The aim of this study was to examine a major oil palm residue, empty fruit bunch (EFB), looking at its effects on oil palm yield and temporal stability of production. EFB is a by-product from palm oil extraction and contains high amounts of lignocellulose and nutrients (Singh et al., 2010). EFB application to oil palm has been shown to increase soil fertility, soil biodiversity, and soil ecosystem processes, yet its effects on crop yield remain unclear (Carron et al., 2012; Comte et al., 2013; Tao et al., 2016). Here, we investigated crop yield performance over 15 years of continuous EFB application with three application rates (30, 60, and 90 t ha^{-1} yr^{-1} for low, medium, and high rates, respectively), and a reference treatment as control, in a field trial in an oil palm plantation in Sumatra, Indonesia (**Figure 1**). EFB applications with low and medium rates were within the range of the application used in nearby commercial plantations, while the high EFB application rate represented a scenario of higher organic matter inputs. The reference treatment followed a standard estate practice of chemical fertilizers without the addition of EFB. The potential effects of climatic conditions and soil properties on crop yield were also examined. We asked (H1) whether different treatments and climatic factors influenced crop yield over time; (H2) whether different treatments affected the temporal stability in crop yield; and (H3) whether the effects of treatment on crop yield were associated with soil organic carbon levels. We hypothesized that compared to the reference treatment, sites with EFB application would either maintain or increase crop yield, and the strength of effects would depend on the application rate of EFB. We further hypothesized that climatic conditions would pose strong effects on crop yield, and that the yield stability over time would be reduced under EFB application. Finally, we expected that EFB application would enhance crop yield by altering soil organic carbon.

Figure 1 inserts here

2. MATERIALS AND METHODS

2.1 Site description

The study was carried out in an oil palm plantation in Sumatra, Indonesia (0° 56'0" N 101°18'0"E). The oil palm plantation was established in 1987 and is certified by the Roundtable on Sustainable Palm Oil (RSPO). The previous land use of this area was tropical lowland secondary forest dominated by *Dipterocarp* species. The climate of this region is described as tropical humid, with a mean temperature of 26.8 °C and average rainfall of 2400 mm year^{-1}. The soils are Inceptisols of Typic Dystrudepts (USDA soil classification system), with the loamy lowland soil class.

2.2 Experimental design

The 15-year trial began in 1998, when the age of oil palms was 11 years. The field trial was established in two adjacent management blocks, in a flat area with limited leaching and runoff. The field trial was composed of five replicate blocks, covering a total area of 36 hectares of 1200 m length and 300 m wide. Each of the five replicate blocks had four treatment plots: Low-EFB treatment (30 t ha^{-1} yr^{-1}, equivalent to 210 kg $palm^{-1}$ yr^{-1}), Medium-EFB treatment (60 t ha^{-1} yr^{-1}, equivalent to 420 kg $palm^{-1}$ yr^{-1}), High-EFB treatment (90 t ha^{-1} yr^{-1}, equivalent to 630 kg $palm^{-1}$ yr^{-1}), and a reference treatment of chemical fertilizers with no EFB application. Each treatment plot was surrounded by 1.5 m ditches to minimize interference from adjacent treatment plots. Each treatment plot was composed of 36 palms located in 4 rows, with a plot size of approximately 80 m length and 40 m wide. The twelve oil palms in the centre of each treatment plot were used as focal palms for crop productivity and soil properties measurements. In the EFB treatment plots, EFB was applied once a year at one side of the harvesting paths, followed by urea application on the top of EFB to accelerate the EFB decomposition. In the reference treatment plots, chemical fertilizers were applied within palm circles twice a year (i.e. during the February-March and September- October periods) throughout the trial period. The application rate, frequency, application location and type of chemical fertilizers are detailed in **Table 1**.

Table 1 inserts here

2.3 Measurements of oil palm yield and soil properties

The fresh fruit bunch weight was used as an indicator for palm oil yield in our study, as there is a fixed ratio between the weight of fresh fruit bunches and extracted palm oil for the same variety of oil palm (Squire, 1986). The fresh fruit bunches from the 12 focal palms at each treatment plot were harvested and weighed each year throughout the trial. The 15-year cumulative yield was the sum of annual yield from five replicate plots of the same treatment.

Soil samples at 0-15 cm depth were collected at palm age of 13, 16, 19, 23, and 26 years (equivalent to 2, 5, 8, 12, and 15 years of application). Soils were taken at the positions beneath the EFB (one side of harvesting paths) in the EFB treatment plots, and at the equivalent positions in the reference treatment plots, in order to examine the localized effects of EFB on soil organic carbon. As chemical fertilizers applied in oil palm plantations have limited spill-over effects (Carron et al., 2016), we assumed that the chemical fertilizers applied within the palm circles in the reference treatment plots have limited influences on soil properties at the nearby harvesting paths. Soils collected from 12 focal palms of each treatment plot at each time point were pooled to determine the soil organic carbon concentration, using the Walkley-Black method (Nelson and Sommers, 1982). The climatic variables including annual values of maximum temperature, minimum temperature, mean temperature, rainfall, and relative humidity were measured at a meteorological station approximately 5 km from the trial site throughout the trial.

2.4 Statistical analysis

We used R 3.2.2 with the *lmer* function in the *lme4* package for statistical analyses (R Core Team, 2016). The three hypotheses were tested: first, whether EFB application and climatic factors influenced crop yield over the application period; second, whether EFB application affected the temporal stability in crop yield; and third, whether EFB application influenced crop yield by altering soil organic carbon levels.

Prior explorations of climatic factors (annual rainfall, air temperature, and relative humidity) were conducted for their potential effects on yield. We examined the effects with one or two years of time lag, as climate conditions may have delayed effects on oil palm yield (Corley and Tinker, 2015). We found that relative humidity was the only climatic factor which showed pronounced effects on crop yield, with lagged effects of two years. We therefore included the relative humidity as a covariate for crop yield. We used linear mixed effects models to examine the effects of treatment and relative humidity on crop yield over time (H1). The fixed effects included relative humidity, the interactions of treatment type and application year, and the quadratic and cubic terms of application year, in order to capture the temporal dynamics of the crop yield. The fixed effects of the initial model in the R syntax were: ~ treatment × year+ treatment × year^2+ treatment × year^3+ humidity. The replicate block was included as a random effect to account for the spatial correlations of treatment plots within the same block. The application year was also included as a random effect to accounted for temporal correlations of the repeated-measured data. We used stepwise deletion by the anova function to drop non-significant variables ($P > 0.05$), before comparing the most parsimonious model with the null model (Zuur et al., 2009). The *post-hoc* analysis was proceeded when the overall difference between the treatment type was observed.

The yield stability over 15 years under the four treatments were examined (H2). The temporal stability of crop yield for each treatment plot was defined as μ / σ, where μ is the temporal mean of crop yield, and σ is the temporal standard deviation of crop yield over 15 years. Treatment with a higher yield stability represents a lower inter-annual yield variability. We compared the yield stability under four treatments using linear mixed effects models, including the replicate block as a random effect.

Lastly, we tested whether the effects of treatment on crop yield were positively associated with soil organic carbon levels (H3), by testing if the treatment type had an effect on soil organic carbon (H3.1), and if soil organic carbon had an effect on crop yield (H3.2). Before testing H3.1, we explored the potential role of climatic factors on soil organic carbon, because climate factors may either affect crop yield by providing favourable conditions for palm growth, or by altering soil organic carbon levels i.e. by affecting litter decomposition and nutrient release with potential time lags (Couteaux et al., 1995). None of the climatic factors significantly explained soil organic carbon, suggesting that climatic factors may directly affect crop yield. Therefore, we did not include climatic factors in the H3.1 model, but included them in the H3.2 model as a covariate for crop yield. To test H3.1, we used a mixed effects model including the interaction of treatment type and application year as fixed effects, specified as ~ treatment × year in the R syntax. The replicate block and application year were included as random effects. For testing H3.2, we included soil organic carbon and relative humidity as fixed effects, specified as ~ soil organic carbon + humidity in the R syntax. The replicate block and application year were included as the random effects. We examined the lagged effects of soil organic carbon for one and two years, because soil properties can have delayed effects on oil palm growth (Fairhurst and Griffiths, 2014).

3. RESULTS AND DISCUSSION

3.1 EFB application effects on crop yield and temporal stability

The cumulative crop yield of the five replicate plots over 15 years was highest under the Medium-EFB treatment (2161 t ha^{-1}), followed by the High-EFB (2137 t ha^{-1}), Low-EFB (2088 t ha^{-1}), and the chemical fertilizer treatment (2040 t ha^{-1}). The annual crop yield marginally differed among the treatments type ($F_{3,202}$= 2.41, *P*= 0.068) (**Figure 2a**). Specifically, the *post-hoc* test showed higher annual crop yield under the Medium-EFB treatment (28.8 ± 0.60 t $ha^{-1}yr^{-1}$) compared to the reference treatment without EFB (27.2 ± 0.51 t $ha^{-1}yr^{-1}$), while no differences were found among Low-EFB, High-EFB, and reference treatments. These results suggest that switching from full chemical fertilizer treatment to the use of EFB as an alternative nutrient source does not result in reduced crop yield. Further, crop yield can be enhanced by the long-term application of EFB with appropriate rates, i.e. the Medium-EFB treatment of 60 t ha^{-1} yr^{-1} in our study. This application rate is within the range of the business-as-usual practice of EFB application in oil palm plantations at our study area. Our findings indicate that the current practice of EFB application is optimal for increasing crop yield, although the response of crop yield to EFB application depends on the application rate. This result is in line with a study in Malaysian oil palm, showing that EFB application at the rate of 44 t ha^{-1} yr^{-1} for ten years resulted in a higher yield than chemical fertilizer treatment, while a lower rate of 22 t ha^{-1} yr^{-1} of EFB application resulted in similar yield to the chemical fertilizer treatment (Abu Bakar et al., 2010). Advancing from the study, our findings further demonstrate that oil palm yield reaches a plateau with EFB application of an optimal rate, but a decline in yield can occur when the EFB is overdosed. The possible underlying mechanisms for this are discussed in the Section 3.2.

Figure 2 inserts here

We observed a pronounced temporal change in annual crop yield over 15 years (**Figure 2a**). Specifically, the annual crop yield decreased from a palm age of 16 years, and reached the lowest production at the age of 20 years. We hypothesized that the temporal stability in crop yield may be reduced under EFB application, due to the temporal fluctuations in EFB decomposition and nutrient mineralization. However, we found that the inter-annual yield stability did not differ between the treatment types ($F_{3,12}$= 2.35, P= 0.12) (**Figure 2b**). Furthermore, we observed that the increase in relative humidity positively influenced crop yield with a lag effect of two years ($F_{1,9}$= 25.8, P < 0.001) (**Figure 3**), suggesting a strong influence of climatic conditions on oil palm yield. Specifically, during the yield decline period, the relative humidity decreased from 84 % to 79 %, the minimum temperature dropped from 22.5 ºC to 17.4 ºC, and the annual rainfall decreased from 2773 mm yr^{-1} to 1955 mm yr^{-1}. This indicates a cooler environment with potential soil water deficiency, which is sub-optimal for oil palm growth and fruit bunch production (Goh, 2000). Similarly, it has been reported that seasonal changes in rainfall explain 55% of yield variations in Malaysian oil palm plantations (Chow, 1992), while inter-annual variations in temperature and rainfall due to El Niño strongly influence oil palm yield (Cadena et al., 2006). Our findings suggest that the effects of climatic conditions on oil palm yield may be more pronounced than the effects of soil management practices. Stronger effects of climatic conditions on yield over crop residue treatment have also been observed in annual cropping systems (Marinari et al., 2015; Rusinamhodzi et al., 2011; Ventrella et al., 2016).

Figure 3 inserts here

3.2 EFB application influences crop yield by increasing soil organic carbon

To understand whether the effects of treatment type on crop yield were associated with soil organic carbon level, we firstly tested if soil organic carbon differed with treatment type (H3.1), and if soil organic carbon levels influenced crop yield (H3.2). We found that soil organic carbon at 0-15 cm depth significantly differed among the treatment types over the application period (**Figure 4a**). Specifically, the *post-hoc* comparisons showed that soil organic carbon was significantly higher under the Medium-EFB treatment (2.16 ± 0.17%; mean ± SE), compared to the reference treatment (1.64 ± 0.14%). Furthermore, soil organic carbon positively explained the annual crop yield with lag effects of two years (**Table 4b**). Both soil organic carbon and the annual crop yield were the highest under the Medium-EFB treatment over the trial period (**Figure 2a, 4a**). These results suggest that EFB application may enhance the annual crop yield by increasing soil organic carbon, especially under the Medium-EFB application rate. Increases in soil organic matter are associated with increased porosity, aggregate stability, hydraulic conductivity, and biological activities, which facilitate nutrient cycling and crop production (Edmeades, 2003; Magdoff and Weil, 2004). The positive effects of soil organic carbon on crop yield have been reported for annual crops, such as wheat, rice, maize, and peas (Lal, 2010). Our results present empirical evidence for a tropical perennial cropping system.

Figure 4 inserts here

Interestingly, the levels of soil organic carbon over the application period were higher under the Medium-EFB treatment, compared to the High-EFB treatment. One possible reason is that the High-EFB treatment had thicker layers of EFB on the surface of the soil, which may create an an-aerobic environment that inhibits microbial decomposition and carbon sequestration. Another explanation is that decomposing EFB can release polyphenol substances, which can be toxic for soil biota, and in turn influence their processes associated with nutrient cycling (Sabrina et al., 2009). Further research is needed to explore this hypothesis. Previous studies in Indonesian and Malaysian oil palm have shown that soil organic carbon increases with higher application rates of EFB, although the EFB application rate examined in those studies were all below the medium application rate of 60 t ha^{-1} yr^{-1} (Abu Bakar et al., 2010; Comte et al., 2013). Together with the results of inhibition of crop yield under the High-EFB treatment, our findings highlight the importance of optimizing application rates of EFB to increase soil organic carbon and crop yield in oil palm cultivation.

4. CONCLUSION

The land area under oil palm cultivation is expected to expand over the coming decades, not only in Southeast Asia, but also in Africa, and South America (Sayer et al., 2012). Identifying and implementing optimal management practices that can conserve soil ecosystem while intensifying crop yield is essential for the sustainable development of oil palm. Application of a major oil palm residue, empty fruit bunch (EFB), has been shown to enhance soil quality and ecosystem functioning (Carron et al., 2012; Tao et al., 2016). However, the effects of EFB application on crop yield and temporal stability, the optimal application schemes for yield performance, and the potential roles of climatic conditions and soil characteristics on crop yield, have been largely unstudied. This study presented empirical evidence from a 15-year trial in Indonesia. The results showed that EFB application either maintained or increased crop yield, compared to the reference treatment with chemical fertilizers as the sole nutrient input. The EFB application rate of 60 t ha^{-1} yr^{-1} resulted in higher crop yield than the reference treatment, and the increase was positively associated with soil organic carbon. The temporal stability of crop yield was similar under EFB application and the reference treatment, while increases in relative humidity positive influenced crop yield with a time lag of two years. These results reinforce the importance of returning crop residues to agricultural fields for replenishing soil carbon and enhancing crop yield, and suggest that the removal of crop residue from the fields for feedstock of biofuel and other uses can have adverse impacts on soil, crop growth, and food security (Liska et al., 2014). However, we note that the decisions on the use of oil palm residues usually involves trade-offs between transportation costs, greenhouse gas emissions, and economic returns (Chang, 2014). With pressure for more sustainable practices within the oil palm industry and changing climatic conditions, optimizing agricultural management practices to maintain soil health will become even more important if intensification of oil palm is to expand in a sustainable manner. We have taken a step in this direction by highlighting the positive effects of crop residue application on yield and temporal stability of oil palm production.

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Figure 1 (a) An empty fruit bunch (EFB) treatment plot at our field trial in an oil palm plantation in Sumatra, Indonesia. The EFB were applied at the sides of the harvesting paths, and urea was applied on the top of EFB layers to facilitate EFB decomposition. (b) A reference treatment plot at our field trial. Chemical fertilizers were applied in the palm circles, without the application of EFB.

Table 1 The application rates of empty fruit bunch (EFB) and chemical fertilizers, and the equivalent nutrient application rates for Low-EFB, Medium-EFB, High-EFB, and the reference treatments.

Code	Treatment	Application rate	Nutrient application rate (kg palm^{-1} yr^{-1})					
		(kg palm^{-1} year^{-1})	C	N	P	K	Mg	Ca
Reference	Chemical fertilizers	Urea 3.5		1.61				
	without the addition of	TSP 1			0.26			0.14
	EFB	MOP 5			0.75	2.50		
		Kieserite 2					0.32	
Low-EFB	Low application rate of	EFB 210	102	0.56	0.064	1.7	0.1	0.1
	EFB with urea	Urea 0.02		0.01				
Medium-EFB	Medium application	EFB 420	204	1.12	0.13	3.4	0.2	0.2
	rate of EFB with urea	Urea 0.04		0.02				
High-EFB	High application rate of	EFB 630	306	1.68	0.19	5.1	0.3	0.3
	EFB with urea	Urea 0.06		0.03				

*The carbon and nutrient composition of EFB were referenced from (Comte et al., 2013; Moradi et al., 2014). EFB: empty fruit bunch; TSP: triple super phosphate ($Ca(H_2PO_4)_2 \bullet H_2O$); MOP: Muriate of Potash, potassium chloride (KCl); Kieserite: magnesium sulfate ($MgSO_4 \cdot H_2O$).

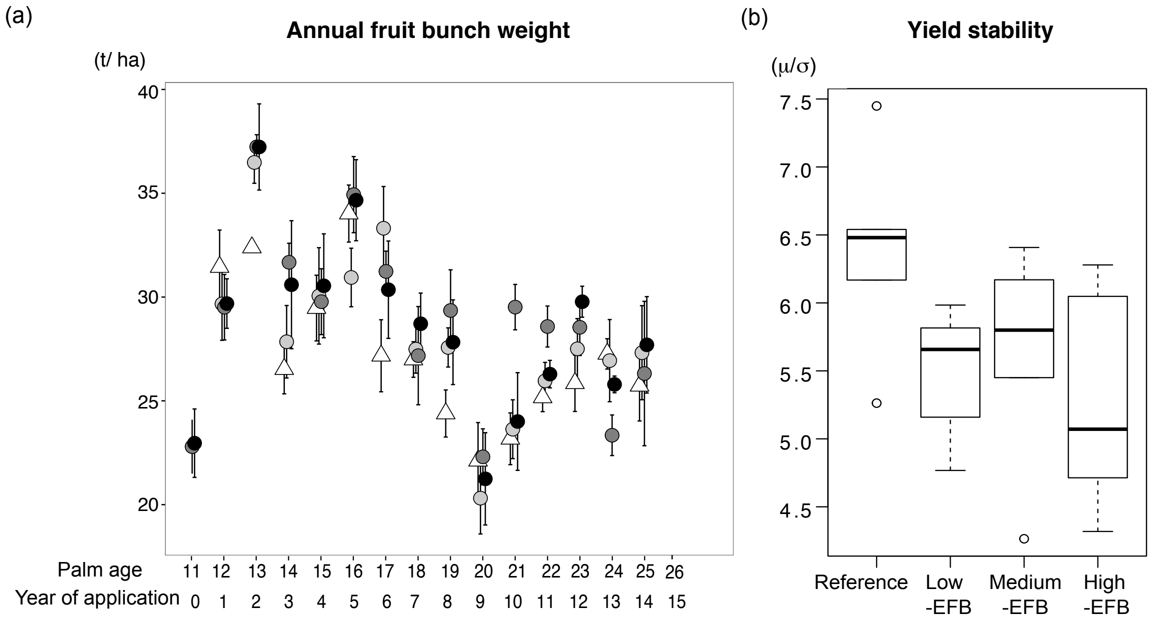

Figure 2 (a) Annual fruit bunch weight (mean± SE, n =5) over 15 years of application under four treatments: Low-EFB treatment (open circle), Medium-EFB treatment (grey circle), High-EFB treatment (black circle), and reference treatment (open triangle). (b) Inter-annual yield stability over 15 years under four treatments, represented as boxplots with median and upper and lower quartiles; the whiskers representing the maximum and minimum values; the dots are outliners. No significant differences in yield stability were detected among the four treatments ($F_{3,12}$= 2.35, P= 0.12). The units for yield stability is μ / σ, where μ is the temporal mean of crop yield, and σ is the temporal standard deviation of crop yield over 15 years.

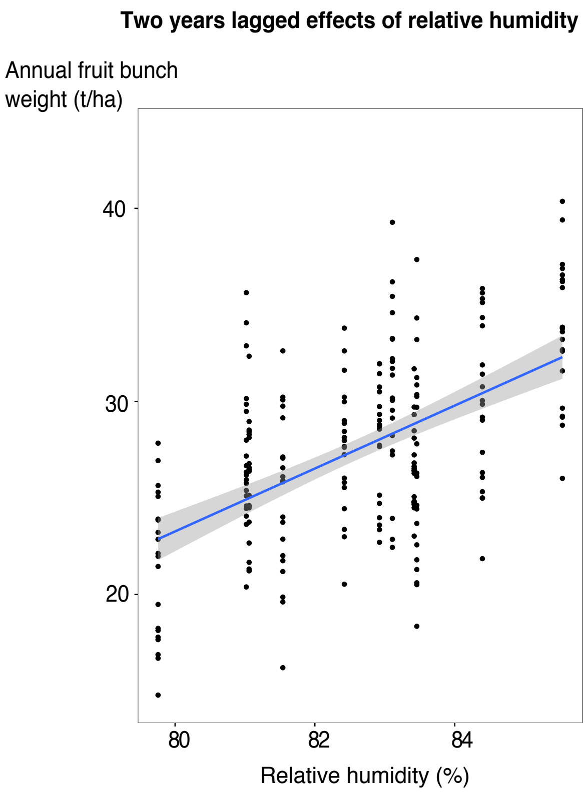

Figure 3 Annual fresh fruit bunch weight in a function of relative humidity with a lag effect of two years ($F_{1,9}$= 25.84, P < 0.001, R^2=0.30).

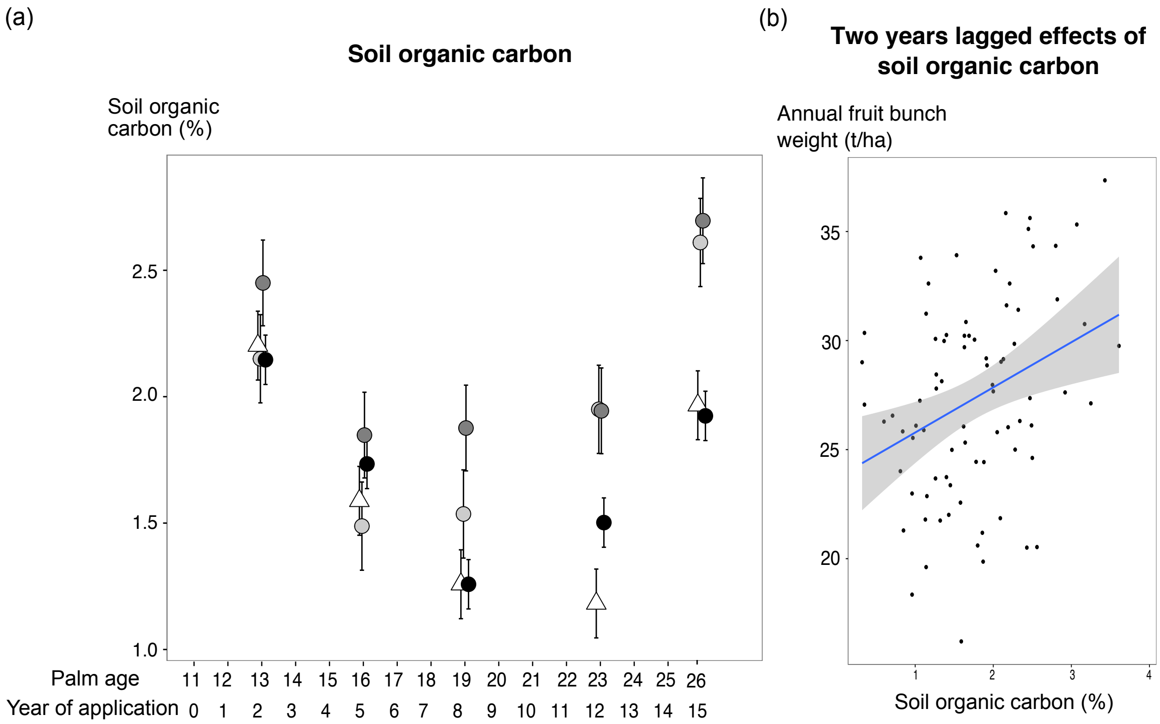

Figure 4 (a) Changes in soil organic carbon (mean± SE, n= 5) over 15 years under four treatments: Low-EFB treatment (open circle), Medium-EFB treatment (grey circle), High-EFB treatment (black circle), and reference treatment (open triangle). (b) The annual fresh fruit bunch weight as a function of soil organic carbon, with a time lag of two years ($F_{1,78}$= 8.4, $P < 0.05$, R^2=0.11).