Oil Palm Industry Economic Journal Vol. 25 (2) September 2025 p. 31-49
DOI: https://doi.org/10.21894/opiej.2025.02

CHALLENGES AND OPPORTUNITIES FOR INTENSIFYING OIL PALM CULTIVATION IN WEST-CENTRAL AFRICA, USING A CASE STUDY OF GHANA

TIEMEN RHEBERGEN[1,2,3]* **and PAUL N. NELSON**[4]

ABSTRACT

The global demand for palm oil, an economically important product in tropical regions, continues to rise rapidly. To meet this demand, there is a focus on expanding oil palm production, particularly in Latin America and Africa. However, in West and Central Africa, biophysical constraints, such as sub-optimal climate conditions and poor management practices, limit yields. Socioeconomic issues, including a lack of skilled labour and disorganised industry expansion, further hinder production. Opportunities for intensification are thus considerable in West Africa, where fresh fruit bunch (FFB) yields are ~56% lower than those of major producers in Southeast Asia and ~47% lower than in Latin America. This study reviewed opportunities for yield intensification in oil palm cultivation, using Ghana as a case study, while considering both agronomic and socio-economic factors. Findings suggest that increases in palm oil production may result from increased fruit supply from smallholders, who are the dominant producers in Ghana (~95%) and promoting specific practices for yield intensification, such as improved harvesting and nutrient management. Increasing average yields to a biophysically achievable 21 t ha^{-1} could significantly boost national FFB production, potentially eliminating the need for additional land, and meeting Ghana's current annual demand for crude palm oil without expansion. Yield intensification strategies could therefore underpin effective strategies for agricultural intensification in Ghana and the broader West-Central Africa region. Achieving this requires collaborative efforts between industry stakeholders, including plantations, smallholders and government intervention.

Keywords: land sparing, plantation, smallholder, yield gap, yield intensification.

Received:18 September 2024**; Accepted:** 2 March 2025**; Published online:** 2 May 2025.

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is an important crop for food production globally and for economic development in tropical regions. More than 80% of palm oil is produced in Indonesia and Malaysia where 90% of the area under oil palm cultivation occurs within 10° of the Equator (Food and Agriculture Organization [FAO], 2023; Lim *et al.*, 2011; Paramananthan, 2003; Rhebergen, 2019). The crop contributes 35%-40% of global vegetable oil production and plays a key role in driving economic development in many tropical regions (Corley, 2009; FAO, 2024; Griffiths *et al.*, 2002; Hansen *et al.*, 2015; Rhebergen, 2019; World Wildlife Fund [WWF], 2022). It is a highly efficient crop in terms of input use, and delivers the highest oil yield among oil-producing crops (De Vries *et al.*, 2010).

Driven by rising global demand for vegetable oil (Corley, 2009), there has been a rapid expansion of the area under oil palm, with the cultivated area expanding from 3.6 million hectares in 1961 to

---

[1] African Plant Nutrition Institute,
C/O IFDC, ICIPE Compound, Nairobi, Kenya.

[2] Plant Production Systems Group,
Wageningen University,
P.O. Box 430, 6700 AK Wageningen,
The Netherlands.

[3] CSIRO Agriculture and Food,
Darwin, NT, 0828, Australia.

[4] College of Science and Engineering,
James Cook University, Cairns, QLD, Australia.

* *Corresponding author e-mail: tiemen.rhebergen@csiro.au*

28.7 million hectares by 2020 (FAO, 2023). Using FAO data, the rate of oil palm expansion over the 2000-2020 period was 983,000 ha yr^{-1}, greater than cocoa (258,000 ha yr^{-1}), rubber (285,000 ha yr^{-1}) and rice (782,000 ha yr^{-1}), but less than soybean (2,707,000 ha yr^{-1}). While the FAO data on vegetable oil production may have various limitations, such as data gaps and inconsistencies, they remain a valuable point of reference (Jannot, 2013). With a continued projected increase in demand for palm oil in the coming decades and limited undeveloped land in Southeast Asia, the industry is expected to expand mostly in Latin America and Africa (Jannot, 2013; Laurance *et al*., 2014; Rhebergen, 2019; Sayer *et al*., 2012). In Africa, expansion is encouraged not only by the availability of low-cost land but also by relatively cheap labour, low taxes and proximity to key markets in Europe and the Middle East (Jannot, 2013). Increases in production to date have been achieved mostly through the expansion of the cultivated area, and average yields remain far below the potential (Donough *et al*., 2009; Rhebergen, 2019; Sayer *et al*., 2012).

Improvements in productivity are critical for addressing challenges including a rapidly changing climate, growing competition for good quality agricultural land and the growing imperative for environmental stewardship (Bryan *et al*., 2014; Rhebergen, 2019; Sayer *et al*., 2012; Tilman *et al*., 2017). Intensification and improvement in resource use efficiency are considered two of the most promising approaches for increasing agricultural productivity (Bryan *et al*., 2014; Khatun *et al*., 2017; Rhebergen, 2019; Sayer *et al*., 2012; Wessel & Quist-Wessel, 2015; Woittiez *et al*., 2017). Such intensification entails bridging the yield gap between current farmer output and the potential yields attainable through best practices and existing technology in a specific environment (Guilpart *et al*., 2017; Lobell *et al*., 2009; Rhebergen, 2019; Sayer *et al*., 2012).

There are considerable opportunities to intensify palm oil production, which will provide net benefits for production and the environment. Although some expansion of the cultivated area may be justified (Corley, 2009), closing 'yield gaps' on land already planted to oil palm will contribute to production whilst avoiding negative environmental impacts associated with expansion (Griffiths & Fairhurst, 2003; Griffiths *et al*., 2002; Rhebergen, 2019; Sayer *et al*., 2012). Yield intensification, together with concomitant conservation of large reserves ('land sparing'), provides greater net production and biodiversity benefits than efforts to maintain biodiversity (apart from that directly beneficial to productivity) within plantations (Phalan *et al*., 2011; Soliman *et al*., 2016). This is contingent upon the implementation of measures related to habitat connectivity (Grass *et al*., 2019). Ecological intensification aims to increase yield per unit of land, approaching the potential yield of farming systems, while maintaining acceptable standards of environmental stewardship (Fairhurst & Griffiths, 2014).

Opportunities for intensification are likely to be large in West and Central Africa, due to low current productivity (*Figure 1*). Despite the Gulf of Guinea in West Africa being considered the centre of origin for oil palm (Simmonds, 1976; Zeven, 1964), the region's current fresh fruit bunch (FFB) yields (average ~8.0 t ha^{-1}) are considerably lower than those in Southeast Asia (average ~18.0 t ha^{-1}) and Latin America (15.0 t ha^{-1}), due to less suitable climatic conditions and suboptimal management practices, particularly among smallholder farmers (FAO, 2023; Paramananthan, 2003; Rhebergen, 2019). Ghana is typical of the West African countries in which oil palm is grown, and distinctly different from the main producing countries, Indonesia and Malaysia (Jannot, 2013; Ruml *et al*., 2022). In Ghana, the oil palm sector is predominantly characterised by smallholder-driven production systems, in contrast to Southeast Asia, where large-scale industrial plantations dominate. The scale of industrial operations in Ghana is comparatively limited, with plantations being significantly smaller. For instance, the largest industrial oil palm plantation in Ghana, the Ghana Oil Palm Development Corporation (GOPDC), spans approximately 15,000 ha across two estates (https://www.gopdc-ltd.com/). By comparison, SD Guthrie in Malaysia operates on a much larger scale, managing nearly 310,000 ha across 121 estates (https://www.sdguthrie.com/).

This review focuses on Ghana as a case study to explore the concept of yield intensification in oil palm through a systems approach that integrates both agronomic and socio-economic perspectives. The results of a four year yield intensification project, implemented by the International Plant Nutrition Institute (IPNI) and Solidaridad West Africa, are synthesised to identify factors limiting palm oil production in the country. Using the yield gap concept, opportunities for increasing production are examined. This article aims to highlight the significance of yield intensification in enhancing the sustainability of oil palm production systems and the livelihoods of those involved.

YIELD GAPS IN OIL PALM

Yield gap analysis has been applied to systematically assess food security and opportunities for increasing production of various crops at various scales (Guilpart *et al*., 2017; Van Ittersum *et al*., 2013). It identifies the factors responsible for yield gaps, and how they might be mitigated, in a two-step process.

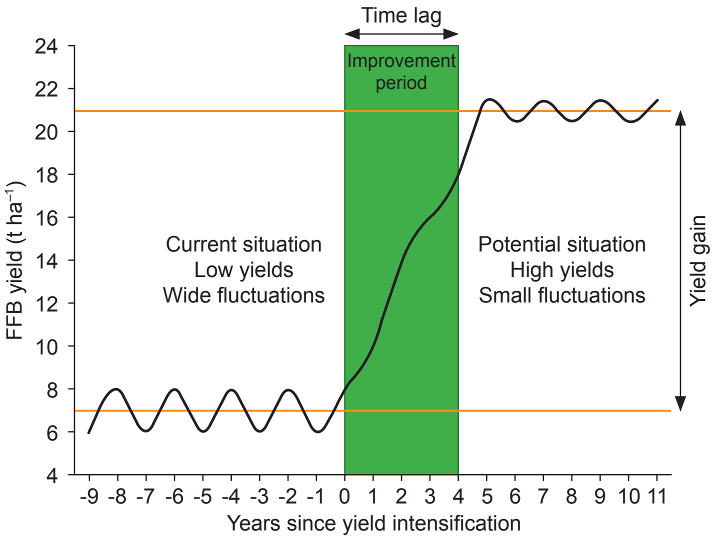
The first step is to quantify the yield gap, which is the difference between the potential yield and the actual yield. Potential yield may be 'non-water-limited' (where sufficient irrigation water is available) or 'water-limited' for rainfed crops. The next step is to identify the factors contributing to the yield gap, which allows remedial measures to be devised and implemented (Lobell, 2013).

Yield gap analysis in oil palm is challenging for several reasons (Hoffmann *et al*., 2017). Most yield gap analyses have been for annual crops such as cassava (Fermont *et al*., 2009), wheat (Aggarwal & Kalra, 1994; Anderson, 2010; Bell *et al*., 1995), rice (Laborte *et al*., 2012; Yang *et al*., 2008) and other cereals (Neumann *et al*., 2010). By comparison, perennial crops have received little attention (Euler *et al*., 2016; Hoffmann *et al*., 2017; Woittiez *et al*., 2017). A modified approach is required because perennial crops are structurally different to annual crops (Rhebergen, 2019; Rhebergen *et al*., 2018). For instance, annual crops allow growers to benefit from new seeds each growing season, while perennial crops have a fixed genetic yield potential for their crop cycle, which lasts at least 25 years for oil palm (Woittiez *et al*., 2017). Additionally, similar to other perennial crops such as rubber, cocoa and coffee, oil palm experiences 6-36 months delay between stressful events and a negative impact on yield (Breure, 2003; Fairhurst & Griffiths, 2014; Rhebergen, 2019). This delay makes it challenging to identify and quantify the effects of specific factors (Rhebergen, 2019; Woittiez *et al*., 2017). For example, a period of water or nutrient stress at any time during flower and fruit development may drastically reduce eventual yield. These time-lagged effects must be accounted for when assessing yield gaps (Hoffmann *et al*., 2017). Moreover, deficiencies in management practices such as incomplete, infrequent, or incorrect harvesting (*i.e.* harvesting unripe or overripe bunches) directly translate to lower yields (Donough *et al*., 2010; Fairhurst & Griffiths, 2014; Rhebergen, 2019). Yield gap assessment in oil palm is further complicated by the disparity in practices among farm types, which range from smallholder farms of <10 ha to large-scale plantations of >10,000 ha (Rhebergen, 2019).

When assessing yield gaps and devising interventions, it is crucial to differentiate between annual and perennial crops. In annual crops, opportunities to close the gaps generally arise between crop cycles. For perennial crops, yield gaps can be addressed within a cropping cycle, though there may be time lags between implementing corrective agronomic measures and observing their effects on yield (*Figure 1*). Additionally, yield gaps might be reduced between crop cycles by using improved germplasm and improving practices employed to establish the crop and manage it during the immature stage (Rhebergen, 2019).

Management regimes that integrate yield intensification with environmental goals are commonly called "Best Management Practices" (BMPs). These are practical and cost-effective agronomic means to reduce the yield gap, while minimising detrimental environmental impacts on production through efficient allocation of resources (Donough *et al*., 2009; Rhebergen, 2019).

In oil palm plantations, considerable work has been carried out to quantify the effect of applying BMPs. To achieve this, a set of site-specific BMPs is identified and applied across several fields or 'blocks' within a mature plantation. These BMPs are evaluated based on agronomic, economic, and environmental criteria compared to reference



Source: Fairhurst *et al*. (2019).

Figure 1. Opportunities to increase palm oil production in Ghana, a country typical of West and Central Africa, are substantial through the implementation of yield intensification strategies.

(or control) fields (REF), where current standard practices are used (Rhebergen, 2019). The yield gaps between BMPs and REF can thus be directly attributed to differences in management practices including crop recovery, pruning, drainage, and use of fertilisers and mill by-products (Oberthür *et al.*, 2012). Implementing and evaluating BMPs involves a trial-and-error approach, where various agronomic practices are modified until the most effective combination for a specific site is determined. It is then scaled up to become standard practice, and the cycle of BMPs identification and assessment begins again (Donough *et al.*, 2009, 2010; Rhebergen, 2019). This process involves close collaboration and active participation from farmers, field staff and managers.

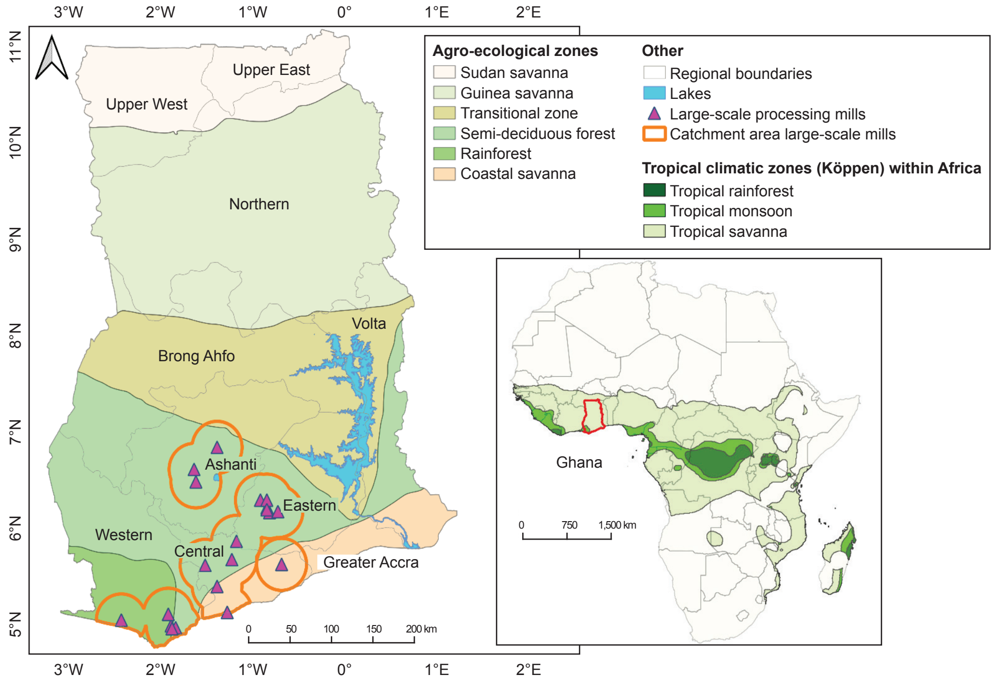
THE SITUATION IN GHANA

Environment

Ghana is biophysically similar to West and Central African countries along the Gulf of Guinea. Its climate is strongly influenced by the inter-tropical convergence zone and its seasonal north-south fluctuation with a dry continental air mass coming from the north and a tropical, maritime air mass from the south (Hayward & Oguntoyinbo, 1987; Rhebergen, 2019). Consequently, the Northern and Southern Regions of Ghana experience distinctly different climates (McSweeney *et al.*, 2010a, 2010b). In order of increasing aridity from south to north, six agro-ecological zones have been identified: Rainforest, semi-deciduous forest, coastal savanna, forest-savanna transition, Guinea savanna and Sudan savanna (Antwi-Agyei *et al.*, 2012) (*Figure 2*).

Oil palm is predominantly cultivated in Southern Ghana, particularly in the tropical rainforest and moist semi-deciduous forest areas, which provide the essential ecological conditions for its growth (Gyasi, 1992; Rhebegren, 2019). Within the oil palm belt, rainfall distribution is bimodal. Long rains occur from March to July, while short rains take place from September to November, with a brief and consistent dry spell in August. The dry season extends from December to February, during which rainfall is typically less than 100 mm in December to February and less than 50 mm in January (Rhebergen, 2019).

Mean annual precipitation is highest in the southwest (~2,400 mm yr^{-1}) and lowest in the north. Relative humidity averages around 80%. The mean monthly temperature rarely falls below 25°C, and the daily variation in temperature is 5°C-9°C. The region's topography is mainly undulating (2°-9°), with rolling to hilly terrain (>20°) in the southwest (Rhebergen, 2019). The primary soil types in the oil palm belt are light texture, highly weathered and leached acrisols and ferralsols (World Reference Base or Ultisols and Oxisols, US Soil Taxonomy), characterised by low pH and poor soil fertility (Buringh, 1979; Rhebergen, 2019; Swaine, 1996).



Source: Rhebergen *et al.* (2016) and Peel *et al.* (2007).

Figure 2. Regions and agro-ecological zones of Ghana, and locations of large-scale oil palm processing mills. The area suitable for oil palm cultivation corresponds more-or-less with the 'Rainforest' and 'Semi-deciduous forest' zones. Inset shows the location of Ghana and tropical climatic zones within Africa.

Palm Oil Production Systems

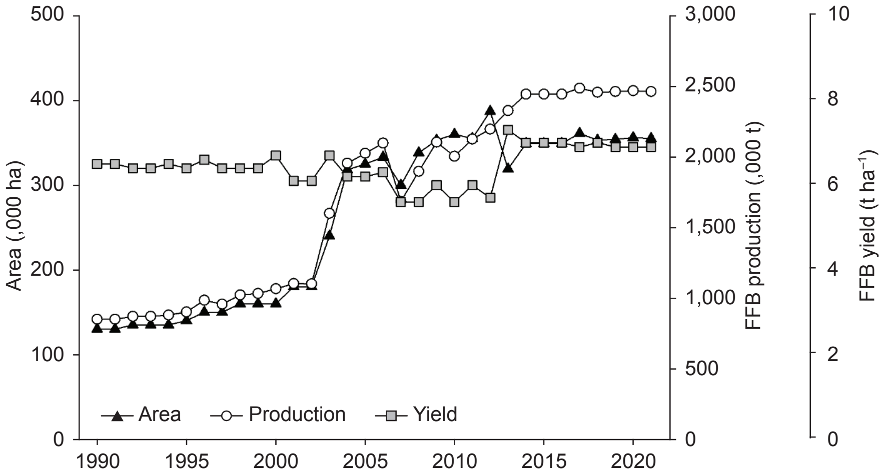
In Ghana and the rest of West and Central Africa, oil palm has been encouraged, spread and cultivated for a long time. The first commercial plantations were established in the 1800s (Gilbert, 2013; Smith *et al.*, 1992), but complex land tenure constrained the development of industrial-scale production (Gyasi, 1996; Jannot, 2013). Consequently, smallholder farmers have historically dominated the oil palm sector in Ghana, serving as the primary drivers of its expansion. However, since the early 2000s, the oil palm sector in Ghana experienced a tremendous surge, partly due to increasing interest from investors in expanding and developing the cultivated area (Rhebergen, 2019). Recent expansion has mostly been due to an increase in the area of large plantations (Ofosu-Budu & Sarpong, 2013), largely at the expense of off-reserve forest patches and food cropland (Asubonteng *et al.*, 2018), but deforestation in reserves by smallholders has also occurred (Acheampong *et al.*, 2019). Although there have been large increases in production over the past 20 years, yield per hectare has remained low (*Figure 3*).

Oil palm is the second largest income-earning crop in Ghana after cocoa (Ofosu-Budu & Sarpong, 2013), and provides a major source of employment (Gilbert, 2013). Although Ghana is the third largest producer of palm oil in sub-Saharan Africa, with an annual production of 2.5 million tonnes in 2021 (next to Nigeria [10.1 million tonnes] and Cameroon [2.6 million tonnes]) (FAO, 2023), it has an annual crude palm oil (CPO) production deficit of ~140,000 t (for 2020), which is partly compensated by costly imports (FAO, 2023). A similar production deficit has developed in other West and Central African countries since the 1990s (Jannot, 2013). Hence, there is a considerable opportunity in Ghana to increase production to meet the high demand for palm oil.

The Ghanaian palm oil industry has three main components: (i) Large corporate plantations (≥1,000 ha) with substantial processing mills (capacity >15 t hr^{-1} of FFB), (ii) smallholder farms of up to 100 ha, and (iii) small-scale processors utilising semi-mechanised mills (capacity of <1 t hr^{-1} of FFB) (Adjei-Nsiah *et al.*, 2012; Rhebergen, 2019). While several censuses show contrasting results (FAO, 2023; MASDAR, 2011; Ofosu-Budu & Sarpong, 2013), it is believed that smallholder farms comprise about 95% of the total area under oil palm in Ghana (~327,600 ha), with the majority of the farms <5 ha, and account for most of the FFB production nationally (>80%) (Rhebergen, 2018, 2019). The remainder of the land area and production is accounted for by large industrial plantations.

Industry Structure

Corporate plantations in Ghana are defined by their large size, monoculture plantings and organised layout (Gyasi, 1996), while the smallholder sector mainly consists of a highly fragmented mosaic of low-yielding small farms amongst other land uses. Moreover, smallholders in Ghana are not well integrated within the whole industry (Dzanku & Hodey, 2022; Fold & Whitfield, 2012; Rhebergen, 2019) compared with the main producing countries such as Malaysia and Indonesia (Jannot, 2013; Rhebergen, 2019; Ruml *et al.*, 2022; Shamsul Bahrin & Lee, 1988). In Ghana, some smallholders are associated with corporate plantations in nucleus-smallholder or out-grower arrangements (5%), but the majority are independent farmers without formal ties to a plantation-milling company (90%) (Adjei-Nsiah *et al.*, 2012; Osei-Amponsah *et al.*, 2012; Ruml *et al.*, 2022). Smallholders affiliated with companies are obliged to sell all their produce to the company mill, and obtain technical support and inputs (*e.g.*, hybrid seedlings and fertilisers) on credit from the company (Rhebergen, 2019).



Source: FAO (2023).

Figure 3. Changes in the area under oil palm, total FFB production and FFB yield in Ghana from 1990-2017.

In contrast, independent smallholders are self-reliant and can sell their FFB to the processing mills either directly or via middlemen, sell on the open market, or process their own FFB into palm oil. Smallholder farmers who are better educated and operate larger farms tend to earn better returns because their scale allows them to overcome the set-up costs required to transport FFB to the mills (Dzanku & Hodey, 2022). In regions with multiple mills nearby, competition for FFB is high, leading to price wars between plantations and local buyers in the domestic consumption market. Additionally, the uncoordinated establishment of new mills near existing ones has exacerbated the competition for FFB, highlighting the need for improved planning within the industry (Fold & Whitfield, 2012) (*Figure 2*).

CURRENT PRODUCTION CONSTRAINTS AND FUTURE OUTLOOK

Biophysical Constraints and Opportunities

Unlike regions in Southeast Asia, such as parts of North Sumatra, Indonesia and Sabah, Malaysia which receive high annual rainfall evenly distributed throughout the year, West Africa experiences lower annual rainfall and regular dry seasons (Carr, 2011). These dry seasons can significantly impact crop yields. Multiple studies have demonstrated that a yield reduction of 10%-15% occurs with each 100 mm increase in water deficit (Corley & Tinker, 2003; Olivin, 1968). However, yield results from a trial conducted at three locations with varying annual water deficits in Ghana indicate that the reduction could be even larger (>20%), as supported by yield simulations using PALMSIM (Hoffmann *et al*., 2014) (*Figure 4*).

This reduction could reach 40%-50% of palms experienced severe water stress the previous year (Caliman & Southworth, 1998). Water deficits exceeding 400 mm yr^{-1} are considered unsuitable for economic oil palm cultivation due to their severe impact on floral initiation, which reduces growth and yield (Danso *et al*., 2008; Manorama *et al*., 2024; Olivin, 1968; Paramananthan, 2013; Van Der Vossen, 1969). These deficits affect nearly 70% of the total land area in Ghana (Rhebergen *et al*., 2016). Oil palm in Ghana is primarily cultivated in areas with annual water deficits of 100-150 mm ("Optimal" zone), and to a greater extent in areas with 150-250 mm annual water deficit ("Favourable" zone) (Rhebergen *et al*., 2016). These zones have a FFB yield potential of approximately 25-30 and 20-25 t ha^{-1} respectively (*Figure 4*). Thus, water deficit largely determines both the maximum achievable yield at a specific location and the cultivable area, serving as a critical constraint to oil palm production in Ghana and across much of West and Central Africa (Jannot, 2013; Rhebergen *et al*., 2016). This may be exacerbated in the future due to climate change-induced droughts driven by increased temperatures, reduced annual rainfall and prolonged dry seasons. However, modelling suggests that anticipated climate changes, marked by rising temperatures and an earlier onset of the rainy season, could lead to improved yields in the Niger Delta Region of Nigeria (Okoro *et al*., 2017). Nonetheless, although there is broad agreement among climate projections concerning regional changes in temperature, there are large uncertainties about future changes in the monsoon system, which drives precipitation in the region (Niang *et al*., 2014; Okoro *et al*., 2017).

Water stress reduces oil palm yield and affects its distribution throughout the year. In regions with well-distributed rainfall, yields remain relatively steady year-round. However, in areas with pronounced dry seasons, such as Ghana, yield peaks are more pronounced, impacting harvesting and processing. To counteract the effects of water stress, irrigation is often recommended and is expected to become increasingly important due to the anticipated rise in drought frequency and intensity, as well as the expansion of oil palm into drier regions (Okoro *et al*., 2017; Woittiez *et al*., 2017).

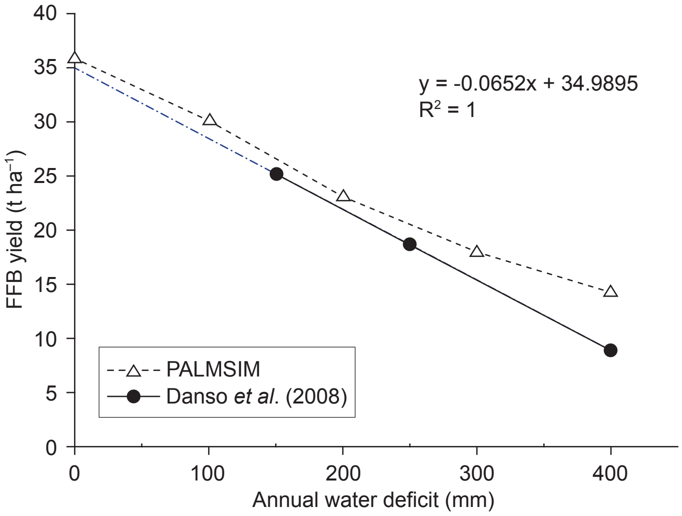
While the impact of drought on oil palm is well-documented, research on yield responses to irrigation remains limited, particularly in West Africa. Under well-watered conditions, crop evapotranspiration (ETc) for mature oil palm is estimated at 4-5 mm day^{-1} or 1,461-1,829 mm yr^{-1}, equivalent to 280-350 L $palm^{-1}$ day^{-1} for a stand density of 143 palms ha^{-1} (Carr, 2011; Dufrene, 1989). In Malaysia, irrigation in oil palm cultivation is considered viable only if it increases yields by at least 4 t ha^{-1} (Lee & Izwanizam, 2013), with reported gains of 5-6 t ha^{-1} achieved through its implementation (Afandi *et al*., 2022).

Similarly, a trial conducted in Ghana's Western Region reported a yield increase of approximately 5.0 t FFB ha^{-1} over three years when irrigation was combined with ample nutrition (Rhebergen *et al*., 2019). In contrast, irrigation alone resulted in a much smaller yield increase of just 0.6 t ha^{-1}. Notably, both treatments received similar amounts of water: 1,796 mm in year 1 (37% from irrigation), 1,803 mm in year 2 (39% from irrigation) and 1,712 mm in year 3 (29% from irrigation) indicating that water availability alone was not the primary limiting factor. These results underscore the critical role of adequate nutrition in maximising the benefits of irrigation (Rhebergen *et al*., 2019).

While the Ghanaian trial's scale was insufficient for a comprehensive cost-benefit analysis, irrigation alone may not be profitable, due to high capital costs (USD2,500 ha^{-1}) and operating costs (USD150 ha^{-1} yr^{-1} for 450 L palm^{-1} day^{-1}) associated with sprinkler irrigation (Tittinutchanon *et al*., [2008] adjusted for inflation). However, combining irrigation with fertiliser could lead to significant profit increases. Optimum fertiliser rates are likely to be higher with irrigation due to higher attainable yields (Tittinutchanon *et al*., 2008), and the optimum fertiliser and irrigation practices will vary based on environmental conditions (Woittiez *et al*., 2017). In cases where irrigation is not economically viable or logistically feasible such as when water sources like rivers are limited or insufficient to sustainably support oil palm cultivation alternative drought mitigation strategies should be considered. These include selecting soils with good water-holding capacity, using organic mulches and reducing plant density (Carr, 2011).

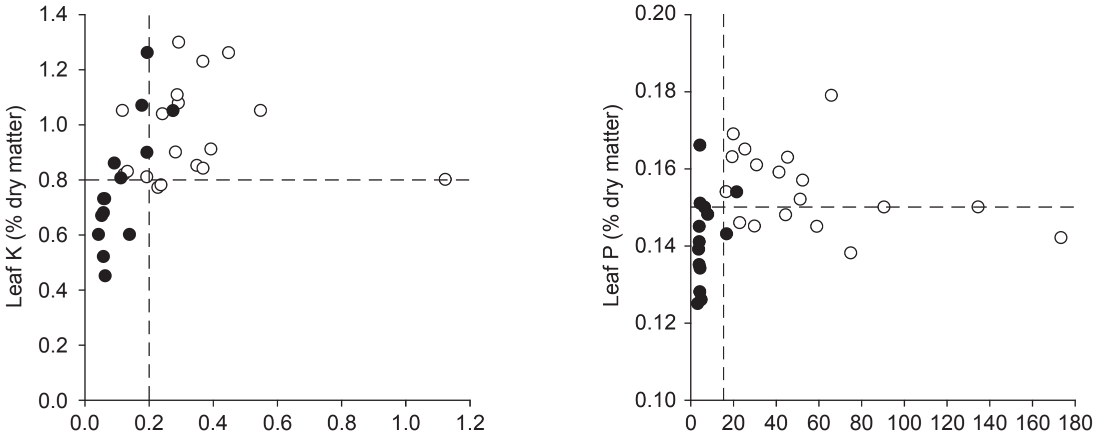
Another challenge for oil palm production in Ghana is inadequate nutrient supply. Soil and leaf analyses reveal significant nutritional constraints, particularly in phosphorus (P) and potassium (K) (*Figure 5*), primarily due to historically low fertiliser applications in plantations and minimal use on smallholder farms.

To sustainably intensify production, these deficiencies must be alleviated. Response to K is likely to be particularly important in Ghana due to its role in mitigating water-stress (Taulya, 2013). Site-specific fertiliser recommendations are currently lacking for oil palm in Ghana and developing them is essential to increase yields. Their development requires fertiliser response trials in different environments and crop phases, as well as consideration of all the other inherent and management factors influencing soil fertility (Nelson, 2023).



Source: Danso *et al*. (2008), Hoffmann *et al*. (2014) and Rhebergen *et al*. (2014).

Figure 4. Relationship between the annual water deficit and yield at three trial sites, and yield simulations using PALMSIM under various water deficit regimes for the oil palm plantation Norpalm Ghana Ltd.



Source: Rhebergen *et al*. (2018).

Figure 5. Low leaf and soil concentrations for K and P indicate considerable nutritional constraints, particularly at smallholder farms (black circles; open circles for plantations). The leaf and soil critical values for K and P are represented by dashed horizontal and vertical lines.

Management Constraints and Opportunities with Yield Intensification

In Ghana, potential (*rainfed*) FFB yields are around 21.0 t ha^{-1}, yet actual yields average approximately 11.0 t ha^{-1} on large corporate plantations and 6.0 t ha^{-1} on smallholdings, resulting in yield gaps of 9.0 and 14.0 t ha^{-1}, respectively (Rhebergen, 2019; Rhebergen *et al*., 2018). These low yields are linked to several challenges, including unfavourable climate conditions, poor soil fertility and inadequate field management (Rhebergen, 2019). Additionally, small-scale processors achieve oil extraction rates (OER) as low as 12%, primarily due to poor processing practices and equipment (*e.g.*, a digester combined with a separate hand-operated screw press [Donker, 1979]), compared to 21% achieved by large-scale processors (*Figure 6*). These inefficiencies further reduce productivity, resulting in potential annual CPO losses of over 5.0 and 3.0 t ha^{-1} yr^{-1} for smallholder and large corporate systems, respectively, during peak production (Rhebergen *et al*., 2018).

Figure 6. Workers operating a hand-press for palm oil extraction, commonly used in small-scale processing systems, achieve lower oil extraction efficiency than large-scale mills.

The potential to increase yields in Ghana by implementing BMPs was thus considerable and led to a four year study that commenced in 2013. Production constraints were identified for twenty smallholder farms and three large-scale plantations (full project description and locations provided in Rhebergen [2019]). Yield improvement with BMPs compared to REF occurred in two distinct phases: i) A short-term effect (≤1 year) resulting from improved operational management, such as maximising crop recovery through harvesting all suitable crops ('yield taking') and ii) a longer-term effect (>1 year) driven by enhanced agronomic practices ('yield making') (Rhebergen *et al*., 2020).

To evaluate the impact of BMPs implementation, various measurements related to crop production (such as bunch count and weight), field maintenance (field audit scores), palm nutrition (fertiliser usage, chemical analysis of leaves and soil) and labour allocation (including man-days dedicated to harvesting and field upkeep) were conducted at regular intervals. A comprehensive depiction of the BMPs process and its associated measurements can be found in Rhebergen (2019).

Results of the study indicated an overall increase in yield of ~7 t ha^{-1} for large plantations and ~12 t ha^{-1} for smallholders, of which ~30% and ~40% were attributed to crop recovery, respectively. Improvements in crop recovery were achieved by implementing more frequent harvesting (with intervals of 7-10 days) and enhancing field access (through better roads, paths and weeded circles), which led to more efficient production (*i.e.*, higher bunch weight harvested per harvester, from a smaller area). Since oil palm produces bunches continuously, it is crucial to maintain complete crop recovery over the whole year. If harvest intervals exceed 10 days, some of the crops may become over-ripe or rotten, leading to losses (Fairhurst & Griffiths, 2014).

The larger yield response on smallholdings was partly due to poor initial field conditions, resulting in a lower baseline yield compared to plantations (5.3 *vs.* 11.1 t ha^{-1}). Most smallholder farms were severely neglected; the absence of harvesting paths and weeded circles restricted access to palms, while poor pruning and frond management hindered workers from harvesting ripe FFB (*Figure 7*). Consequently, the potential for improvement and benefits of crop recovery were greater than in plantations.

Long-term yield increases were more challenging to explain due to the delayed impact of improved agronomic practices on yield. However, an analysis of fertiliser use, leaf nutrients and soil chemistry identified significant nutritional constraints, especially in P and K, which need careful management to build and maintain soil fertility and enhance production, particularly on smallholder farms. Yield increases with improved agronomy were thus substantial, even though fertiliser recommendations were not fully implemented. Fertiliser applications were larger at both plantation and smallholder sites; however, they were not adequately balanced to align with BMPs program recommendations. This led to significant nutrient gaps between the recommended and applied rates, resulting in notable leaf nutrient deficiencies, particularly for P and K. Among smallholder farmers, limited access to credit and the delayed return on investment from fertilisers were the major barriers. For plantations, financial constraints, such as insufficient budgets for fertiliser inputs, or conflicts with BMPs program priorities, were cited as the primary reasons for these discrepancies (Rhebergen, 2019).

The largest yields recorded in the study were 27.3 t ha^{-1} at a plantation site, 25.0 t ha^{-1} at a smallholder farm, and 32.6 t ha^{-1} at an irrigation trial (Rhebergen *et al.*, 2019). These results demonstrate the immense production potential that can be achieved by minimising agronomic and biophysical constraints through various yield intensification techniques.

Figure 7. The greatest yield improvements in rehabilitating smallholder oil palm farms were achieved by facilitating unrestricted access for harvesting and palm maintenance. This was accomplished through the creation of weeded harvest paths and circles and the pruning of unproductive fronds. a) Before rehabilitation and b) after rehabilitation.

Socioeconomic Constraints and Opportunities at the Farm Scale

Smallholdings are typically family-operated (Mensah-Bonsu *et al.*, 2009). In these households, economically active members work on the farm for an average of only 61 days yr^{-1} (Dzanku & Hodey, 2022). A significant portion of household income is derived from non-crop activities, as off-farm employment often offers better financial returns, albeit with limited opportunities. Labour allocation is heavily influenced by commercialisation levels, with more commercialised smallholder households dedicating a higher proportion of their labour to farm activities (Dzanku & Hodey, 2022). However, the financial barriers to adopting advanced practices and technologies remain a major constraint for most smallholders, limiting their potential to improve productivity (Rhebergen, 2019).

In contrast, plantations in Ghana rely heavily on hired labour (Gyasi, 1996). To raise productivity, the importance of improved crop recovery, through frequent harvesting and good access, was highlighted earlier. However, sustaining these operations presents several challenges for plantations:

Insufficient skilled workers. While oil palm plantations provide numerous employment opportunities, the work (particularly harvesting) is often perceived as physically demanding and hazardous (Ismail, 2013; Rhebergen, 2019). Unattractive working conditions, such as isolation and low wages, combined with competition from alternative sectors like large-scale agribusiness and mining, may lead to high turnover rates. Frequent workforce changes and the need for continuous training result in skill shortages, hindering the consistent implementation of BMPs, particularly in maintaining high harvesting standards (Rhebergen, 2019).

Seasonal labour mismatches. Labour demand fluctuates with seasonal crop cycles. During periods of low FFB production, fewer workers are required and piece-rate payments lead many labourers to seek alternative employment. Conversely, during peak production months, the increased demand for harvesters often exceeds supply. Poor planning and recruitment exacerbate these shortages (Panyin, personal communication, 2024), leading to extended harvest intervals and significant crop losses (*Figure 8*). Seasonal production variations also strain milling operations, resulting in underutilisation during the lean season and insufficient capacity during peak periods (Rhebergen, 2019).

Mechanisation offers a way to address some of the labour challenges by reducing the physical burden of field operations and improving productivity (Rhebergen, 2019). Devices designed to collect and transport FFB such as mechanical grabbers, compact transporters, mechanical buffaloes, battery-powered wheelbarrows and loose fruit collectors along with the development of lighter, more ergonomic and powered FFB cutters, could enhance efficiency while improving worker health and safety (Abd Rahim *et al.*, 2010; Anon, 2004; Jayaselan & Ahmad, 2011; Leng, 2002; Murphy, 2014).

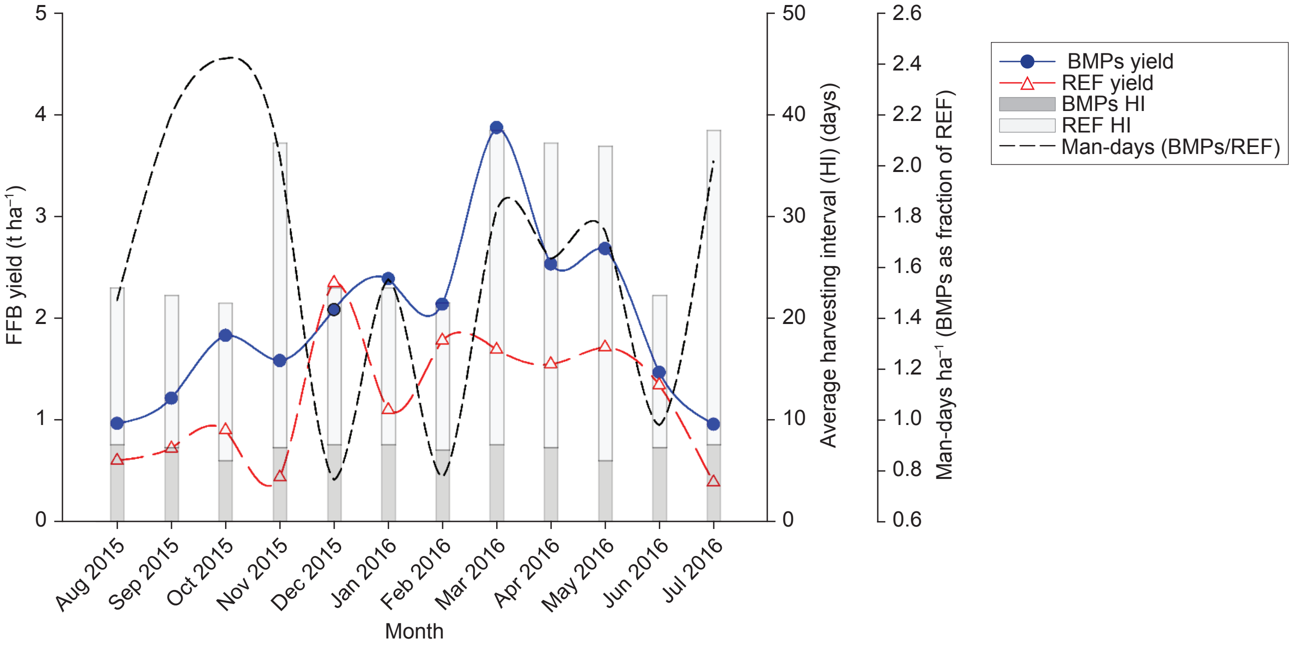


Figure 8. Monthly yield (t ha^{-1}) distribution, average monthly harvesting intervals (HI day^{-1}) and man-days (BMPs expressed as a fraction of REF) for reference (REF) plantings, representing current standard practices and plantings under best management practices (BMPs), which employed improved yield intensification strategies. Data from a yield intensification study at Norpalm Ghana Ltd. (year 3) show that during peak production months (February-May 2016), adequate labour for harvesting and maintaining harvest intervals of 7-10 days is critical to minimising crop losses. BMPs plots achieved a FFB yield of 23.9 t ha^{-1} compared to 14.8 t ha^{-1} for REF plots, where consistent harvest teams were employed in BMPs plots, while REF plots faced labour shortages during peak periods.

Despite its benefits, mechanisation has not been widely adopted in many regions. In Malaysia, only a few of the innovations-primarily for crop evacuation have been adopted, mainly by large plantation groups. Even then, their use is often restricted to areas suitable for machine access and operations (Donough, personal communication, 2024).

In Ghana and other African countries, mechanisation is even less prevalent. Smallholders face prohibitive costs in acquiring tools and equipment, while plantations face additional challenges such as limited access to spare parts and a lack of skilled personnel for machinery maintenance. These factors discourage investment in mechanisation. Moreover, some plantations remain reluctant to mechanise, citing the availability of manual labour as sufficient. Low daily wages and labour rates compared to mechanisation costs further diminish its perceived necessity (Panyin, personal communication, 2024; Tarigan, personal communication, 2024). Similar barriers exist in Malaysia, where a skills deficit among machine operators and support staff persists (Donough, personal communication, 2024).

While mechanisation in the oil palm sector has progressed, there remains significant potential for improvement (Abd Rahim *et al*., 2010). FFB harvesting, in particular, presents challenges such as assessing fruit ripeness and cutting heavy FFB from heights of 10-20 m (Murphy, 2014). Alternative strategies, such as breeding shorter, high-yielding palms, could facilitate harvesting (Arolu *et al*., 2016; Murphy, 2009). These palms could also improve land-use efficiency through increased planting density, higher per-hectare yields and extended crop cycles, thereby reducing replanting costs (Zulkifli *et al*., 2017).

Although mechanisation could bring significant benefits to Ghana's oil palm industry, it must be approached with caution. The sector plays a crucial role in providing economic and social benefits through rural employment, and mechanisation might be viewed as a threat to job opportunities. However, the goal of mechanisation is to enhance productivity within the existing workforce (Abd Rahim *et al*., 2010; Anon, 2004). Addressing social and labour sensitivities requires effective consultation, education and the development of tailored mechanisation strategies. A well-planned and coordinated implementation program is essential for long-term success (Anon, 2004).

Socioeconomic Constraints and Opportunities at the Industry Scale

Expansion of the area under oil palm in Ghana is likely to occur mostly through an increase in the number and size of smallholdings rather than an expansion of large corporate plantations (Rhebergen *et al*., 2014). This is because the establishment of large new plantations is limited by the availability of contiguous tracts of land due to complex land tenure systems (Ruml *et al*., 2022). Expansion of the smallholder sector will have socioeconomic and environmental benefits (Sayer *et al*., 2012). The corporate sector also benefits, as the profitability of processing mills associated with large plantations increases with throughput, even if the FFB comes from smallholders.

Thus, the main opportunities for increased palm oil production are from increased FFB supply from smallholders and yield improvement strategies. These strategies include improving crop recovery through unimpeded field access and maintaining regular harvesting intervals (HI) of 7-10 days and ensuring balanced palm nutrition. Combined, these measures have demonstrated an average yield increase of 61% reaching 17.9 t ha^{-1} in plantations, and 232%, reaching 17.6 t ha^{-1} in smallholder farms (Rhebergen *et al*., 2020), highlighting their significant potential.

Increasing yield from current levels to 21.0 t ha^{-1} would increase national FFB production by 4.8 million tonnes across the smallholder and plantation sectors or enable the same production from an area almost 800,000 ha smaller (*Table 1*). Achieving that yield increase would result in a total annual CPO production of approximately 1.4 million tonnes (assuming an OER of 21%), which is more than adequate to meet Ghana's current demand of 140,000 t yr^{-1} (FAO, 2023) without additional land. Smallholder farmers in Ghana generally express a desire to intensify production (Acheampong *et al*., 2021, 2022).

There is thus considerable scope for improving overall production through better integration of the corporate and smallholder sectors. While contractual arrangements between smallholders and plantation companies may, in some cases, be unfavourable to the smallholders, they could also offer benefits and opportunities that are essential for the development of commercially viable smallholder production systems (Sayer *et al*., 2012). Improved connections between smallholder farmers and the corporate sector could offer an effective way to address key constraints to increasing yields, such as limited knowledge of good management practices, inadequate infrastructure and restricted access to high-quality seedlings, agronomic inputs, credit and technical support (Rhebergen, 2019).

Poor road infrastructure is a major constraint to agricultural development in Africa (Acheampong *et al*., 2018). In Ghana, many oil palm cultivation areas lack access roads, and during peak harvest seasons, which coincide with heavy rains, unsurfaced or neglected roads become impassable. This leads to FFB spoilage and income losses for farmers (MASDAR, 2011). The inefficiency of road networks affects the entire value chain, from transporting FFB to mills to distributing palm oil and other by-products (Asante, 2023). Inadequate roads also raise transport costs and reduce logistics efficiency, impacting profitability by increasing travel time and causing breakdowns (MASDAR, 2011). Furthermore, rural populations, particularly women, face significant challenges in marketing their products due to the lack of all-weather roads, and relying on labour-intensive methods like head-loading, which exacerbate post-harvest losses (MASDAR, 2011). The poor state of roads also limits smallholder farmers' ability to engage in contract farming, hindering income stability and excluding them from the technology adoption, training and innovation needed to increase productivity (Acheampong *et al*., 2018; Wongnaa *et al*., 2024). Study conducted in the oil palm belt of Ghana has shown that improving road infrastructure and providing agronomic inputs result in better market integration, higher yields and reduced pressure to expand into forests (Acheampong *et al*., 2018, 2021).

Milling-plantation companies, which rely on securing a sufficient crop supply, could support smallholder oil palm growers by providing inputs and advice. These companies could offer inputs such as fertilisers, agrochemicals, tools and quality seedlings on credit, with repayment tied to future crop deliveries, following practices observed in other regions (*Figure 9*) (Rhebergen, 2019). Additionally, milling-plantation companies could play a crucial role in enhancing regional transportation networks, such as through the construction and maintenance of roads, as demonstrated by Ghana Oil Palm Development Company Ltd. (GOPDC) (Huddleston & Tonts, 2007). This improvement would not only benefit the oil palm industry, but also stimulate other industries in the region.

TABLE 1. IMPACT OF OIL PALM YIELD INTENSIFICATION ON PRODUCTION OR LAND AREA IN GHANA

Sector	Current situation			Production situations with yield improvement strategies					
				Target yield = 18.0 t ha^{-1}			Target yield = 21.0 t ha^{-1}		
	Area (ha)	Yield (t ha^{-1})	Production (t)	Production (t)	Production increase (t)	Land saved (ha)	Production (t)	Production increase (t)	Land saved (ha)
Smallholder	311,000	6.0	1,866,000	5,598,000	3,732,000	622,000	6,531,000	4,665,000	777,500
Plantation	16,600	11.0	182,600	298,800	116,200	10,564	348,600	166,000	15,091
Total	**327,600**		**2,048,600**	**5,896,800**	**3,848,200**	**632,564**	**6,879,600**	**4,831,000**	**792,591**

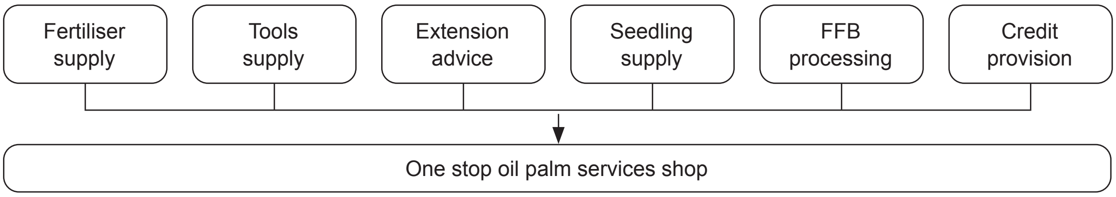


Figure 9. Large corporate mills can serve as one-stop shops to provide services and inputs for smallholders in Ghana.

To monitor smallholder production effectively and to identify yield gaps on a larger scale, it is essential to collect farm data and then collate and analyse it using a database such as Agrisoft Systems' Oil Palm Management Program (OMP) (Agrisoft Systems, 2018; Rhebergen, 2019). This approach can also help milling companies offer targeted advice to growers for yield improvement and mitigate the risks associated with providing loans. Improvements to infrastructure (particularly feeder roads to the farm) may also be provided by milling-plantation companies due to mutual benefits. Currently, more commercialised smallholder households are better off in some but not all aspects of welfare (Dzanku & Hodey, 2022), but voluntary implementation of the changes suggested here will enhance the benefits of intensification among smallholder producers. Optimal integration of the smallholder and corporate sectors will require careful collaborative design, taking into account the Ghanaian context and the needs of smallholders with little political power (Khatun *et al*., 2020; Naess & Chinsinga, 2022; Ruml *et al*., 2022).

In addition to integrating smallholders with mills, coordination through farmers' groups or smallholder schemes has considerable potential to increase production and optimise expansion. Enabling institutional arrangements may advantage smallholder participation in supply chains and substantially increase their productivity (Dzanku & Hodey, 2022; Jelsma *et al*., 2017). Coordinating smallholder farmers into consolidated cooperatives, similar to the smallholder schemes used in Malaysia and Indonesia, could help transition from the current mosaic landscape to conserving large, contiguous areas of native vegetation. This approach, shifting from 'land sharing' to 'land sparing' (Green *et al*., 2005), has been demonstrated to enhance biodiversity conservation in multiple-use regions (Edwards *et al*., 2010; Fitzherbert *et al*., 2008; Phalan, 2018; Phalan *et al*., 2009, 2011). However, such a shift would require effective supporting policies and a significant reform of land tenure.

Evidence suggests that the increased commercialisation of smallholder farming in Ghana facilitated by improved road access has contributed to a decline in deforestation (Acheampong *et al*., 2018). This is because better market integration and higher input use have led to increased yields on existing farmland, reducing the pressure to expand cultivation into forested areas (Acheampong *et al*., 2018). In contrast, Abman and Lundberg (2024) suggest that improved market access facilitated through production contracts, in which smallholders receive credit to establish production, a guaranteed price and quantity for the contract duration, and output pickup at the village may increase deforestation. It is therefore essential to recognise that intensification alone does not guarantee land sparing and conservation. In fact, intensification may increase financial incentives for forest clearing and oil palm expansion if higher yields and profitability increase the opportunity costs of conserving land (Laurance *et al*., 2014; Phelps *et al*., 2013).

Furthermore, if the demand for palm oil is elastic, higher yields could lead to increased production targets, thereby encouraging further expansion into agricultural land (Green *et al*., 2005). For instance, even if the palm oil supply increases, it may not reduce prices, thereby maintaining the incentive to cultivate more land. Conversely, a decrease in prices might also drive land expansion to sustain income levels (Baudron & Giller, 2014). Therefore, efforts to ecologically intensify production should be accompanied by the implementation of policies and practices to strategically optimise the allocation of land for conservation and agriculture (Asubonteng *et al*., 2018; Laurance *et al*., 2014; Sayer *et al*., 2012). Successful examples of such integration exist in Ghana (Acheampong *et al*., 2020).

In summary, promoting specific practices for yield intensification, particularly among smallholders, is recommended, along with fostering better integration between smallholder and corporate sectors through arrangements that ensure fairness to smallholders. These recommendations correspond closely with those given by Sayer *et al.* (2012) to improve the sustainability of palm oil production globally, including the attainment of the best possible outcomes for the carbon cycle and biodiversity conservation. There has been much recent discussion about the benefits of sustainability certification for oil palm farmers, especially the Roundtable on Sustainable Palm Oil (RSPO). The inclusion of smallholders in certification schemes subscribed by plantation companies may help improve smallholder productivity and welfare, but there are many challenges to effective implementation, including high transaction costs (Brako *et al*., 2021; Djama, 2018; Nelson, 2023). The approaches discussed here may be facilitated by sustainability certification but will have a positive impact on smallholder productivity and well-being with or without certification (Ogahara *et al*., 2022).

CONCLUSION

The Ghanaian oil palm industry faces numerous challenges, primarily related to low productivity and disorganised expansion. Productivity is limited by dry climate and poor soil fertility, low inputs, shortage of labour and poor infrastructure (especially transport) and services. Additionally, the expansion of large-scale plantations is constrained by limited available land and complex land tenure systems. To address these challenges, production increases must be pursued through intensification and yield increases on smallholder farms. However, this presents a significant challenge, as smallholders are poorly organised and not yet effectively integrated into the palm oil supply system. Policies, organisational models and implementation pathways suitable for increasing overall productivity in Ghana's complex oil palm sector should be explored. Future study should, therefore, focus on investigating options to foster institutional arrangements that benefit both smallholder and plantation agriculture in Ghana. This will necessitate coordinated efforts from both industry stakeholders (plantations and smallholders) and government bodies.

ACKNOWLEDGEMENT

We extend our gratitude to the staff of Benso Oil Palm Plantation (BOPP), Norpalm Ghana Ltd., Twifo Oil Palm Plantations (TOPP) and Solidaridad West Africa for their help with the work. Our thanks also go to Chris Donough, Thomas Fairhurst, Ken Giller, Thomas Oberthür, Edward Kofi Panyin, Perdata Tarigan, Anthony Whitbread and Shamie Zingore. This work was supported by K+S Kali GmbH, Canpotex International Pte Limited, Solidaridad, and the International Plant Nutrition Institute (GBL-53).

REFERENCES

Abd Rahim, S., Mohd Ramdhan, K., & Mohd Solah, D. (2010). Enhancing field mechanization in oil palm management. *Oil Palm Bulletin*, *61*, 1–10.

Abman, R., & Lundberg, C. (2024). Contracting, market access and deforestation. *Journal of Development Economics*, *168*, 103269. https://doi.org/10.1016/j.jdeveco.2024.103269

Acheampong, E. O., Macgregor, C. J., Sloan, S., & Sayer, J. (2019). Deforestation is driven by agricultural expansion in Ghana's forest reserves. *Scientific African*, *5*, e00146. https://doi.org/10.1016/j.sciaf.2019.e00146

Acheampong, E. O., Sayer, J., & Macgregor, C. J. (2018). Road improvement enhances smallholder productivity and reduces forest encroachment in Ghana. *Environmental Science & Policy*, *85*, 64–71. https://doi.org/10.1016/j.envsci.2018.04.001

Acheampong, E. O., Sayer, J., Macgregor, C. J., & Sloan, S. (2020). Application of landscape approach principles motivates forest fringe farmers to reforest Ghana's degraded reserves. *Forests*, *11*(4), 411. https://doi.org/10.3390/f11040411

Acheampong, E. O., Sayer, J., Macgregor, C. J., & Sloan, S. (2021). Factors influencing the adoption of agricultural practices in Ghana's forest-fringe communities. *Land*, *10*(3), 266. https://doi.org/10.3390/land10030266

Acheampong, E. O., Sloan, S., Sayer, J., & Macgregor, C. J. (2022). African forest-fringe farmers benefit from modern farming practices despite high environmental impacts. *Land*, *11*(2), 145. https://doi.org/10.3390/land11020145

Adjei-Nsiah, S., Sakyi-Dawson, O., & Kuyper, T. W. (2012). Exploring opportunities for enhancing innovation in agriculture: The case of oil palm production in Ghana. *Journal of Agricultural Science*, *4*(10), 212–223. https://doi.org/10.5539/jas.v4n10p212

Afandi, A. M., Zulkifli, H., Nur Zuhaili, H. A. Z. A., Norliyana, Z. Z., Hisham, H., Saharul, A. M., Dzulhelmi, M. N., & Vu Thanh, T. A. (2022). Oil palm water requirement and the need for irrigation in dry Malaysian areas. *Journal of Oil Palm Research*, *35*(3), 391–405. https://doi.org/10.21894/jopr.2022.0052

Aggarwal, P. K., & Kalra, N. (1994). Analyzing the limitations set by climatic factors, genotype, and water and nitrogen availability on productivity of wheat II. Climatically potential yields and management strategies. *Field Crops Research*, *38*(2), 93–103. https://doi.org/10.1016/0378-4290(94)90003-5

Agrisoft Systems. (2018). *Software solutions for precision agriculture*. http://www.agrisoft-systems.com

Anderson, W. K. (2010). Closing the gap between actual and potential yield of rainfed wheat: The impacts of environment, management, and cultivar. *Field Crops Research, 116*(1–2), 14–22. https://doi.org/10.1016/j.fcr.2009.11.016

Anon. (2004). Plantation mechanisation: Critical success factors. *The Planter, 80*, 417–419.

Antwi-Agyei, P., Fraser, E. D. G., Dougill, A. J., Stringer, L. C., & Simelton, E. (2012). Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield, and socioeconomic data. *Applied Geography, 32*(2), 324–334. https://doi.org/10.1016/j.apgeog.2011.06.010

Arolu, I. W., Rafii, M. Y., Marjuni, M., Hanafi, M. M., Sulaiman, Z., Rahim, H. A., Kolapo, O. K., Abidin, M. I. Z., Amiruddin, M. D., Kushairi Din, A., & Nookiah, R. (2016). Genetic variability analysis and selection of *pisifera* palms for commercial production of high-yielding and dwarf oil palm planting materials. *Industrial Crops and Products, 90*, 135–141. https://doi.org/10.1016/j.indcrop.2016.06.006

Asante, K. T. (2023). The politics of policy failure in Ghana: The case of oil palm. *World Development Perspectives, 31*, 100509. https://doi.org/10.1016/j.wdp.2023.100509

Asubonteng, K., Pfeffer, K., Ros-Tonen, M., Verbesselt, J., & Baud, I. (2018). Effects of tree-crop farming on land-cover transitions in a mosaic landscape in the Eastern Region of Ghana. *Environmental Management, 62*, 529–547. https://doi.org/10.1007/s00267-018-1060-3

Baudron, F., & Giller, K. E. (2014). Agriculture and nature: Trouble and strife? *Biological Conservation, 170*, 232–245. https://doi.org/10.1016/j.biocon.2013.12.009

Bell, M., Fischer, R., Byerlee, D., & Sayre, K. (1995). Genetic and agronomic contributions to yield gains: A case study for wheat. *Field Crops Research, 44*(2–3), 55–65. https://doi.org/10.1016/0378-4290(95)00049-6

Brako, D. E., Richard, A., & Alexandros, G. (2020). Do voluntary certification standards improve yields and wellbeing? Evidence from oil palm and cocoa smallholders in Ghana. *International Journal of Agricultural Sustainability, 19*(1), 16–39. https://doi.org/10.1080/14735903.2020.1807893

Breure, C. (2003). The search for yield in oil palm: Basic principles. In T. Fairhurst & R. Härdter (Eds.), *The oil palm – Management for large and sustainable yields* (pp. 59–98). International Plant Nutrition Institute (IPNI) and International Potash Institute (IPI).

Bryan, B. A., King, D., & Zhao, G. (2014). Influence of management and environment on Australian wheat: Information for sustainable intensification and closing yield gaps. *Environmental Research Letters, 9*(4), 044005. https://doi.org/10.1088/1748-9326/9/4/044005

Buringh, P. (1979). *Introduction to the study of soils in tropical and subtropical regions* (3rd ed.). Centre for Agricultural Publishing and Documentation.

Caliman, J. P., & Southworth, A. (1998, September 23–25). *Effect of drought and haze on the performance of oil palm* [Paper presentation]. International Oil Palm Conference: Commodity of the Past, Today, and the Future, Bali, Indonesia.

Carr, M. K. V. (2011). The water relations and irrigation requirements of oil palm (*Elaeis guineensis*): A review. *Experimental Agriculture, 47*(4), 629–652. https://doi.org/10.1017/s0014479711000494

Corley, R. H. V. (2009). How much palm oil do we need? *Environmental Science & Policy, 12*(2), 134–139. https://doi.org/10.1016/j.envsci.2008.10.011

Corley, R. H. V., & Tinker, P. B. (2003). *The oil palm* (4th ed.). Blackwell Science Ltd.

Danso, I., Nuertey, B. N., Andoh-Mensah, E., Osei-Bonsu, A., & Asamoah, T. E. O., (2008). Response of oil palm to planting density and water deficit in three climatic zones of Southern Ghana. *Journal of Ghana Science Association, 10*(2), 93–102. https://doi.org/10.4314/jgsa.v10i2.18045

De Vries, S. C., Van De Ven, G. W., Van Ittersum, M. K., & Giller, K. E. (2010). Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass and Bioenergy, 34*(5), 588–601. https://doi.org/10.1016/j.biombioe.2010.01.001

Djama, M. (2018). Certifying sustainability in oil palm cultivation. In A. Rival (Ed.), *Achieving sustainable cultivation of oil palm* (Vol. 2, pp. 315–329). Burleigh Dodds Science Publishing.

Donker, P. (1979). A hand-operated screw press for extracting palm oil. *Appropriate Technology, 5*(4), 18–20.

Donough, C. R., Witt, C., & Fairhurst, T. H. (2009). Yield intensification in oil palm plantations through best management practices. *Better Crops with Plant Food, 93(1),* 12–14.

Donough, C. R., Witt, C., & Fairhurst, T. H. (2010). Yield intensification in oil palm using BMP as a management tool. *Better Crops International, 94*, 1–8.

Dufrene, E. (1989). *Photosynthese, consommation en eau et modelisation de la production chez le palmier à huile (*Elaeis guineensis *Jacq.)* [Doctoral dissertation, Université Paris-Sud Orsay].

Dzanku, F. M., & Hodey, L. S. (2022). *Livelihood outcomes of agricultural commercialisation, women's empowerment and rural employment* (APRA Working Paper 92).

Edwards, D. P., Hodgson, J. A., Hamer, K. C., Mitchell, S. L., Ahmad, A. H., Cornell, S. J., & Wilcove, D. S. (2010). Wildlife-friendly oil palm plantations fail to protect biodiversity effectively. *Conservation Letters, 3*, 236–242. https://doi.org/10.1111/j.1755-263X.2010.00107.x

Euler, M., Hoffmann, M. P., Fathoni, Z., & Schwarze, S. (2016). Exploring yield gaps in smallholder oil palm production systems in Eastern Sumatra, Indonesia. *Agricultural Systems, 146*, 111–119. https://doi.org/10.1016/j.agsy.2016.04.007

Fairhurst, T., & Griffiths, W. (2014). *Oil palm: Best management practices for yield intensification*. International Plant Nutrition Institute and Tropical Crop Consultants Limited.

Fairhurst, T., Griffiths, W., & Rankine, I. (2019). *Oil palm – Agronomy*. Tropical Crop Consultants Limited.

Food and Agriculture Organization (FAO). (2023). *FAOSTAT database*. https://www.fao.org/faostat/en/#home

Food and Agriculture Organization (FAO). (2024). *FAOSTAT database*. https://www.fao.org/faostat/en/#home

Fermont, A. M., Van Asten, P. J. A., Tittonell, P., Van Wijk, M. T., & Giller, K. E. (2009). Closing the cassava yield gap: An analysis from smallholder farms in East Africa. *Field Crops Research*, *112*(1), 24–36. https://doi.org/10.1016/j.fcr.2009.01.009

Fitzherbert, E., Struebig, M., Morel, A., Danielsen, F., Bruhl, C., Donald, P., & Phalan, B. (2008). How will oil palm expansion affect biodiversity? *Trends in Ecology & Evolution*, *23*(10), 538–545. https://doi.org/10.1016/j.tree.2008.06.012

Fold, N., & Whitfield, L. (2012). *Developing a palm oil sector: The experiences of Malaysia and Ghana compared* (DIIS Working Paper 2012:08). Danish Institute for International Studies.

Gilbert, D. (2013). Oil palm and palm oil industry in Ghana: A brief history. *International Research Journal of Plant Science, 4*(6), 158–167.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., Tiede, J., Udy, K., Westphal, C., Wurz, A., & Tscharntke, T. (2019). Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People and Nature*, *1*(2), 262–272. https://doi.org/10.1002/pan3.21

Green, R. E., Cornell, S. J., Scharlemann, J. P. W., & Balmford, A. (2005). Farming and the fate of wild nature. *Science*, *307*(5709), 550–555. https://doi.org/10.1126/science.1106049

Griffiths, W., & Fairhurst, T. H. (2003). Implementation of best management practices in an oil palm rehabilitation project. *Better Crops International*, *17*(1), 16–19.

Griffiths, W., Fairhurst, T., Rankine, I., Kerstan, A., & Taylor, C. (2002, July 8–12). *Identification and elimination of yield gaps in oil palm: Use of OMP7 and GIS* [Paper presentation]. International Oil Palm Conference and Exhibition, Bali, Indonesia.

Guilpart, N., Grassini, P., Sadras, V. O., Timsina, J., & Cassman, K. G. (2017). Estimating yield gaps at the cropping system level. *Field Crops Research*, *206*, 21–32. https://doi.org/10.1016/j.fcr.2017.02.008

Gyasi, E. A. (1992). Emergence of a new oil palm belt in Ghana. *Tijdschrift Voor Economische En Sociale Geografie*, *83*(1), 39–49. https://doi.org/10.1111/j.1467-9663.1992.tb00607.x

Gyasi, E. A. (1996). The environmental impact and sustainability of plantations in Sub-Saharan Africa: Ghana's experiences with oil-palm plantations. In E. A. Gyasi & J. Uitto (Eds.), *Sustaining the future: Economic, social and environmental change in Sub-Saharan Africa* (pp. 342–357). United Nations University Press.

Hansen, S. B., Padfield, R., Syayuti, K., Evers, S., Zakariah, Z., & Mastura, S. (2015). Trends in global palm oil sustainability research. *Journal of Cleaner Production*, *100*, 140–149. https://doi.org/10.1016/j.jclepro.2015.03.051

Hayward, D. F., & Oguntoyinbo, J. S. (1987). *The climatology of West Africa*. Hutchinson.

Hoffmann, M. P., Vera, A. C., Van Wijk, M. T., Giller, K. E., Oberthür, T., Donough, C., & Whitbread, A. M. (2014). Simulating potential growth and yield of oil palm (*Elaeis guineensis*) with PALMSIM: Model description, evaluation and application. *Agricultural Systems*, *131*, 1–10. https://doi.org/10.1016/j.agsy.2014.07.006

Hoffmann, M. P., Donough, C. R., Cook, S. E., Fisher, M. J., Lim, C. H., Lim, Y. L., Cock, J., Kam, S. P., Mohanaraj, S. N., Indrasuara, K., Tittinutchanon, P., & Oberthür, T. (2017). Yield gap analysis in oil palm: Framework development and application in commercial operations in Southeast Asia. *Agricultural Systems*, *151*, 12–19. https://doi.org/10.1016/j.agsy.2016.11.005

Huddleston, P., & Tonts, M. (2007). Agricultural development, contract farming and Ghana's oil palm industry. *Geography*, *92*(3), 266–278. https://doi.org/10.1080/00167487.2007.12094205

Ismail, A. (2013). The effect of labour shortage in the supply and demand of palm oil in Malaysia. *Oil Palm Industry Economic Journal, 13*(2), 15–26.

Jannot, C. (2013). Les filières oléagineuses en Afrique de l'Ouest et du Centre: Le grand retour du palmier à huile. In *Déméter 2014: Économie et stratégies agricoles* (pp. 247–312). Club Déméter.

Jayaselan, H. A. J., & Ahmad, D. (2011). Development of a mechanization selection system for oil palm plantations with alternative planting patterns. *Journal of Oil Palm Research*, *23*, 990–998. http://psasir.upm.edu.my/id/eprint/23045/

Jelsma, I., Slingerland, M., Giller, K. E., & Bijman, J. (2017). Collective action in a smallholder oil palm production system in Indonesia: The key to sustainable and inclusive smallholder palm oil? *Journal of Rural Studies*, *54*, 198–210. https://doi.org/10.1016/j.jrurstud.2017.06.005

Khatun, K., Maguire-Rajpaul, V. A., Asante, E. A., & McDermott, C. L. (2020). From agroforestry to agroindustry: Smallholder access to benefits from oil palm in Ghana and the implications for sustainability certification. *Frontiers in Sustainable Food Systems*, *4*. https://doi.org/10.3389/fsufs.2020.00029

Khatun, R., Reza, M. I. H., Moniruzzaman, M., & Yaakob, Z. (2017). Sustainable oil palm industry: The possibilities. *Renewable and Sustainable Energy Reviews*, *76*, 608–619. https://doi.org/10.1016/j.rser.2017.03.077

Laborte, A. G., De Bie, K., Smaling, E. M. A., Moya, P. F., Boling, A. A., & Van Ittersum, M. K. (2012). Rice yields and yield gaps in Southeast Asia: Past trends and future outlook. *European Journal of Agronomy*, *36*(1), 9–20. https://doi.org/10.1016/j.eja.2011.08.005

Laurance, W. F., Sayer, J., & Cassman, K. G. (2014). Agricultural expansion and its impacts on tropical nature. *Trends in Ecology & Evolution*, *29*(2), 107–116. https://doi.org/10.1016/j.tree.2013.12.001

Lee, C. T., & Izwanizam, A. (2013). Lysimeter studies and irrigation of oil palm in some inland soils of Peninsular Malaysia-FELDA's experience. *The Planter, 89*(1042), 15–29.

Leng, T. (2002). Mechanisation in oil palm plantations: Achievement and challenges. *Malaysian Oil Science and Technology, 11*(2), 70–77.

Lim, K. H., Goh, K. J., Kee, K. K., & Henson, I. E. (2011). Climatic requirements of oil palm. In K. J. Goh, S. B. Chiu, & S. Paramananthan (Eds.), *Agronomic principles & practices of oil palm cultivation* (p. 771). Agricultural Crop Trust (ACT).

Lobell, D. B. (2013). The use of satellite data for crop yield gap analysis. *Field Crops Research*, *143*, 56–64. https://doi.org/10.1016/j.fcr.2012.08.008

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, *34*, 179–204. https://doi.org/10.1146/annurev.environ.041008.093740

Manorama, K., Reddy, G. P. O., Suresh, K., Ray, S. S., Behera, S. K., Kumar, N., & Mathur, R. K. (2024). Characterization and mapping of the potential area of oil palm using multi-criteria decision analysis in a geographic information systems environment. *Agriculture*, *14*(7), 986. https://doi.org/10.3390/agriculture14070986

MASDAR. (2011). *Ghana's oil palm master plan: Final report*.

McSweeney, C., New, M., & Lizcano, G. (2010a). *UNDP climate change country profiles: Ghana*. Retrieved July 9, 2015, from http://country-profiles.geog.ox.ac.uk/

McSweeney, C., New, M., Lizcano, G., & Lu, X. (2010b). The UNDP climate change country profiles: Improving the accessibility of observed and projected climate information for studies of climate change in developing countries. *Bulletin of the American Meteorological Society, 91*, 157–166.

Mensah-Bonsu, A., Amegashie, D. P., & Gyasie, S. (2009). The structure of labour market and demand for hired labour for oil palm production in the western region of Ghana. *Journal of Science and Technology (Ghana), 29*(3), 102–113. https://doi.org/10.4314/just.v29i3.50059

Murphy, D. J. (2009). Oil palm: Future prospects for yield and quality improvements. *Lipid Technology*, *21*(11–12), 257–260. https://doi.org/10.1002/lite.200900067

Murphy, D. J. (2014). The future of oil palm as a major global crop: Opportunities and challenges. *Journal of Oil Palm Research, 26*(1), 1–24.

Naess, L. O., & Chinsinga, B. (2022). *The Political Economy of Agricultural Commercialisation: Insights from Crop Value Chain Studies in sub-Saharan Africa*. https://doi.org/10.19088/apra.2022.020

Nelson, P. N. (2023). Sustainable soil management in tropical agriculture. In S. Jayaraman, R. C. Dalal, & R. Lal (Eds.), *Sustainable soil management – Beyond food production* (pp. 204–239). Cambridge Scholars Publishing.

Neumann, K., Verburg, P. H., Stehfest, E., & Müller, C. (2010). The yield gap of global grain production: A spatial analysis. *Agricultural Systems*, *103*(5), 316–326. https://doi.org/10.1016/j.agsy.2010.02.004

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). Africa. In V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1199–1265). Cambridge University Press.

Oberthür, T., Donough, C. R., Indrasuara, K., Dolong, T., & Abdurrohim, G. (2012). Successful intensification of oil palm plantations with best management practices: Impacts on fresh fruit bunch and oil yield. *The Planter, 89*, 185–216.

Ofosu-Budu, K., & Sarpong, D. (2013). Oil palm industry growth in Africa: A value chain and smallholders study for Ghana. In A. Elbehri (Ed.), *Rebuilding West Africa's food potential* (pp. 349–389). FAO/IFAD.

Ogahara, Z., Jespersen, K., Theilade, I., & Nielsen, M. R. (2022). Review of smallholder palm oil sustainability reveals limited positive impacts and identifies key implementation and knowledge gaps. *Land Use Policy*, *120*, 106258. https://doi.org/10.1016/j.landusepol.2022.106258

Okoro, S. U., Schickhoff, U., Boehner, J., Schneider, U. A., & Huth, N. I. (2017). Climate impacts on palm oil yields in the Nigerian Niger Delta. *European Journal of Agronomy*, *85*, 38–50. https://doi.org/10.1016/j.eja.2017.02.002

Olivin, J. (1968). Étude pour la localisation d'un bloc industriel de palmiers à huile II. Le critère de jugement. *Oléagineux, 23*(8–9), 499–504.

Osei-Amponsah, C., Visser, L., Adjei-Nsiah, S., Struik, P. C., Sakyi-Dawson, O., & Stomph, T. J. (2012). Processing practices of small-scale palm oil producers in the Kwaebibirem District, Ghana: A diagnostic study. *NJAS - Wageningen Journal of Life Sciences*, *60–63*(1), 49–56. https://doi.org/10.1016/j.njas.2012.06.006

Paramananthan, S. (2003). Land selection for oil palm. In R. Härdter & T. H. Fairhurst (Eds.), *Oil palm – Management for large and sustainable yields* (pp. 27–58). Potash & Phosphate Institute/Potash & Phosphate Institute of Canada (PPI/PPIC) and International Potash Institute (IPI).

Paramananthan, S. (2013). Managing marginal soils for sustainable growth of oil palms in the tropics. *Journal of Oil Palm & the Environment, 4*, 1–16.

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, *11*(5), 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Phalan, B., Fitzherbert, E. B., Rafflegeau, S., Struebig, M. J., & Verwilghen, A. (2009). Conservation in oil palm landscapes. *Conservation Biology*, *23*(2), 244–245. https://doi.org/10.1111/j.1523-1739.2008.01151.x

Phalan, B., Onial, M., Balmford, A., & Green, R. E. (2011). Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. *Science*, *333*(6047), 1289–1291. https://doi.org/10.1126/science.1208742

Phalan, B. T. (2018). What have we learned from the land sparing-sharing model? *Sustainability*, *10*(6), 1760. https://doi.org/10.3390/su10061760

Phelps, J., Carrasco, L. R., Webb, E. L., Koh, L. P., & Pascual, U. (2013). Agricultural intensification escalates future conservation costs. *Proceedings of the National Academy of Sciences*, *110*(19), 7601–7606. https://doi.org/10.1073/pnas.1220070110

Rhebergen, T. (2019). *Yield gap analysis in oil palm production systems in Ghana* [PhD dissertation, Wageningen University & Research]. Wageningen, The Netherlands.

Rhebergen, T., Fairhurst, T., Giller, K. E., & Zingore, S. (2019). The influence of water and nutrient management on oil palm yield trends on a large-scale plantation in Ghana. *Agricultural Water Management*, *221*, 377–387. https://doi.org/10.1016/j.agwat.2019.05.003

Rhebergen, T., Fairhurst, T., Whitbread, A., Giller, K. E., & Zingore, S. (2018). Yield gap analysis and entry points for improving productivity on large oil palm plantations and smallholder farms in Ghana. *Agricultural Systems*, *165*, 14–25. https://doi.org/10.1016/j.agsy.2018.05.012

Rhebergen, T., Fairhurst, T., Zingore, S., Fisher, M., Oberthür, T., & Whitbread, A. (2016). Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. *European Journal of Agronomy*, *81*, 1–14. https://doi.org/10.1016/j.eja.2016.08.004

Rhebergen, T., Hoffmann, M., Zingore, S., Oberthür, T., Acheampong, K., Dwumfour, G., Zutah, V., Adu-Frimpong, C., Ohipeni, F., & Fairhurst, T. (2014, June 17–19). *The effects of climate, soil and oil palm management practices on yield in Ghana* [Paper presentation]. International Oil Palm Conference (IOPC), Bali, Indonesia.

Rhebergen, T., Zingore, S., Giller, K. E., Frimpong, C. A., Acheampong, K., Ohipeni, F. T., Panyin, E. K., Zutah, V., & Fairhurst, T. (2020). Closing yield gaps in oil palm production systems in Ghana through best management practices. *European Journal of Agronomy*, *115*, 126011. https://doi.org/10.1016/j.eja.2020.126011

Ruml, A., Chrisendo, D., Iddrisu, A. M., Karakara, A. A., Nuryartono, N., Osabuohien, E., & Lay, J. (2022). Smallholders in agro-industrial production: Lessons for rural development from a comparative analysis of Ghana's and Indonesia's oil palm sectors. *Land Use Policy*, *119*, 106196. https://doi.org/10.1016/j.landusepol.2022.106196

Sayer, J., Ghazoul, J., Nelson, P., & Boedhihartono, A. K. (2012). Oil palm expansion transforms tropical landscapes and livelihoods. *Global Food Security*, *1*(2), 114–119. https://doi.org/10.1016/j.gfs.2012.10.003

Shamsul Bahrin, T., & Lee, B. T. (1988). *Three decades of evolution*. FELDA.

Simmonds, N. W. (Ed.). (1976). *The evolution of crop plants*. Longman.

Smith, N. J. H., Williams, J. T., Plucknett, D., & Talbot, J. P. (1992). *Tropical forests and their crops*. Cornell University Press.

Soliman, T., Lim, F. K. S., Lee, J. S. H., & Carrasco, L. R. (2016). Closing oil palm yield gaps among Indonesian smallholders through industry schemes, pruning, weeding and improved seeds. *Royal Society Open Science*, *3*(8), 160292. https://doi.org/10.1098/rsos.160292

Swaine, M. D. (1996). Rainfall and soil fertility as factors limiting forest species distributions in Ghana. *Journal of Ecology*, *84*(3), 419–428. https://doi.org/10.2307/2261203

Taulya, G. (2013). East African highland bananas (*Musa* spp. AAA-EA) 'worry' more about potassium deficiency than drought stress. *Field Crops Research*, *151*, 45–55. https://doi.org/10.1016/j.fcr.2013.07.010

Tilman, D., Clark, M., Williams, D. R., Kimmel, K., Polasky, S., & Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. *Nature*, *546*(7656), 73–81. https://doi.org/10.1038/nature22900

Tittinutchanon, P., Nakharin, C., Clendon, J. H., & Corley, R. H. V. (2008). A review of 15 years of oil palm irrigation research in Southern Thailand. *The Planter, 84*(989), 537–546.

Van Der Vossen, H. A. M. (1969). Areas climatically suitable for optimal oil palm production in the forest zone of Ghana. *Ghana Journal of Agricultural Science, 2*(2), 113–118.

Van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance - A review. *Field Crops Research*, *143*, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

Wessel, M., & Quist-Wessel, P. M. F. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS - Wageningen Journal of Life Sciences*, *74–75*(1), 1–7. https://doi.org/10.1016/j.njas.2015.09.001

Woittiez, L. S., Van Wijk, M. T., Slingerland, M., Van Noordwijk, M., & Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy*, *83*, 57–77. https://doi.org/10.1016/j.eja.2016.11.002

Wongnaa, C. A., Addai, P., Quainoo, P., Ohene-Yankyera, K., Tham-Agyekum, K. E., & Awunyo-Vitor, D. (2024). Unlocking sustainable partnerships: Exploring the willingness of oil palm producers to engage in contract farming initiatives. *International Journal of Social Economics*. https://doi.org/10.1108/ijse-03-2024-0284

World Wildlife Fund (WWF) (2022). *8 things to know about palm oil*. https://www.wwf.org.uk/updates/8-things-know-about-palm-oil

Yang, W., Peng, S., Laza, R. C., Visperas, R. M., & Dionisio-Sese, M. L. (2008). Yield gap analysis between dry and wet season rice crop grown under high-yielding management conditions. *Agronomy Journal*, *100*(5), 1390–1395. https://doi.org/10.2134/agronj2007.0356

Zeven, A. C. (1964). On the Origin of the oil palm (*Elaeis Guineensis* Jacq.). *Grana Palynologica*, *5*(1), 121–123. https://doi.org/10.1080/00173136409429132

Zulkifli, Y., Norziha, A., Naqiuddin, M. H., Fadila, A. M., Nor Azwani, A. B., Suzana, M., Samsul, K. R., Ong-Abdullah, M., Singh, R., Parveez, G. K. A. & Kushairi, A. (2017). Designing the oil palm of the future. *Journal of Oil Palm Research, 29*(4), 440–455. https://doi.org/10.21894/jopr.2017.00015