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Review article

Yield gaps in oil palm: A quantitative review of contributing factors

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ABSTRACT

Oil palm, currently the world's main vegetable oil crop, is characterised by a large productivity and a long life span (≥25 years). Peak oil yields of 12 t ha^{-1} yr^{-1} have been achieved in small plantations, and maximum theoretical yields as calculated with simulation models are 18.5 t oil ha^{-1} yr^{-1}, yet average productivity worldwide has stagnated around 3 t oil ha^{-1} yr^{-1}. Considering the threat of expansion into valuable rainforests, it is important that the factors underlying these existing yield gaps are understood and, where feasible, addressed. In this review, we present an overview of the available data on yield-determining, yield-limiting, and yield-reducing factors in oil palm; the effects of these factors on yield, as measured in case studies or calculated using computer models; and the underlying plant-physiological mechanisms. We distinguish four production levels: the potential, water-limited, nutrient-limited, and the actual yield. The potential yield over a plantation lifetime is determined by incoming photosynthetically active radiation (PAR), temperature, atmospheric CO_2 concentration and planting material, assuming optimum plantation establishment, planting density (120–150 palms per hectares), canopy management (30–60 leaves depending on palm age), pollination, and harvesting. Water-limited yields in environments with water deficits >400 mm year^{-1} can be less than one-third of the potential yield, depending on additional factors such as temperature, wind speed, soil texture, and soil depth. Nutrient-limited yields of less than 50% of the potential yield have been recorded when nitrogen or potassium were not applied. Actual yields are influenced by yield-reducing factors such as unsuitable ground vegetation, pests, and diseases, and may be close to zero in case of severe infestations. Smallholders face particular constraints such as the use of counterfeit seed and insufficient fertiliser application. Closing yield gaps in existing plantations could increase global production by 15–20 Mt oil yr^{-1}, which would limit the drive for further area expansion at a global scale. To increase yields in existing and future plantations in a sustainable way, all production factors mentioned need to be understood and addressed.

Contents

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1. Introduction

African oil palm (*Elaeis guineensis* Jacq.) has its centre of origin in the humid lowland tropics of West Africa. Wild oil palms are uncommon in primary forests but rather grow in disturbed and very wet locations, such as swamps and river banks, where sunlight is abundant and water available throughout the year (Zeven, 1967). The oil palm is a member of the monocotyledonous palm family (*Arecaceae*). The woody stem carries a single terminal growing point, from which leaves appear at regular intervals in a double spiral (Rees, 1964). Each leaf supports a single inflorescence, which can be either male or female. The harvested product is a fruit bunch comprising 1500–2000 fruitlets. Crude palm oil (CPO) is extracted from the orange-yellow mesocarp, and palm kernel oil (PKO) from the white kernel.

Over the last 100 years, oil palm has changed from a smallholder agroforestry crop and ornamental palm into the world's most important vegetable oil crop. Current worldwide production is estimated at 63 Mt crude palm oil per year, or 36% of the total world vegetable oil production (USDA, 2014). Expansion of oil palm plantations has been suggested as a key cause of deforestation in both Indonesia (Carlson et al., 2012; Stibig et al., 2014) and Malaysia (Miettinen et al., 2011; Stibig et al., 2014), although other drivers such as logging also play a major role (Laurance, 2007; Lambin et al., 2001). The increasing demand for palm oil over the coming decades will probably be met both through expansion of the area planted and increased productivity (Carter et al., 2007; Corley, 2009).

Since oil palm expansion may lead to the displacement of biodiverse rainforests (Gaveau et al., 2014), increased productivity, combined with targeted expansion into degraded areas (Fairhurst and McLaughlin, 2009), are the preferred strategies to meet the growing demand for palm oil. Increasing productivity does not, *per se*, lead to reduction in deforestation unless supporting policies are in place and are properly enforced (Angelsen, 2010), but is a necessary step towards reducing pressure on land. A thorough understanding and quantification of the contribution of different production factors to oil palm yield is urgently needed to estimate the scope to increase productivity in existing stands, and in ongoing (re)planting programs.

Yield gap analysis has been commonly used as a tool to explore the possibilities for improving land productivity (Lobell et al., 2009; van Ittersum et al., 2013; see also www.yieldgap.org). The 'yield gap' is defined as the difference between potential and actual yield (van Ittersum and Rabbinge, 1997), with the upper limit of productivity per hectare being the 'potential yield'. This potential yield is defined as the theoretical yield at a given temperature, ambient atmospheric CO_2 concentration, and incoming photosynthetically active radiation (PAR), with optimum agronomic management and without water, nutrient, pest and disease limitations (van Ittersum and Rabbinge, 1997). It refers to current germplasm or to the best currently available material.

Yield gap analysis has been carried out for a range of annual crops such as wheat (Aggarwal and Kalra, 1994; Bell et al., 1995; Anderson, 2010), cassava (Fermont et al., 2009), rice (Yang et al., 2008; Laborte et al., 2012), and cereals in general (Neumann et al., 2010). A limited number of perennial cropping systems has been subjected to yield gap analysis, including coffee (Wairegi and Asten, 2012), highland banana (Wairegi et al., 2010), and cocoa (Zuidema et al., 2005). Perennial crops such as oil palm are structurally different from annual crops in several ways. In annual crops, growers can take advantage of new seeds with each growing season. By contrast, the yield potential for perennial crops, with a lifespan of up to several decades, is fixed for each planting cycle. Events early in the plantation lifetime, especially in the nursery and at planting, may have strong effects on yield in later years, which complicates the interpretation of yield data (Breure and Menendez, 1990). In addition, oil palm fruit bunches take several years to develop, and there is a time lag of 20–30 months between the onset of stress factors and their impact on yield. This makes it difficult to separate and quantify the effects of individual factors (Adam et al., 2011).

Quantitative data on yield responses of oil palm to different production factors, particularly planting density, irrigation, and fer-