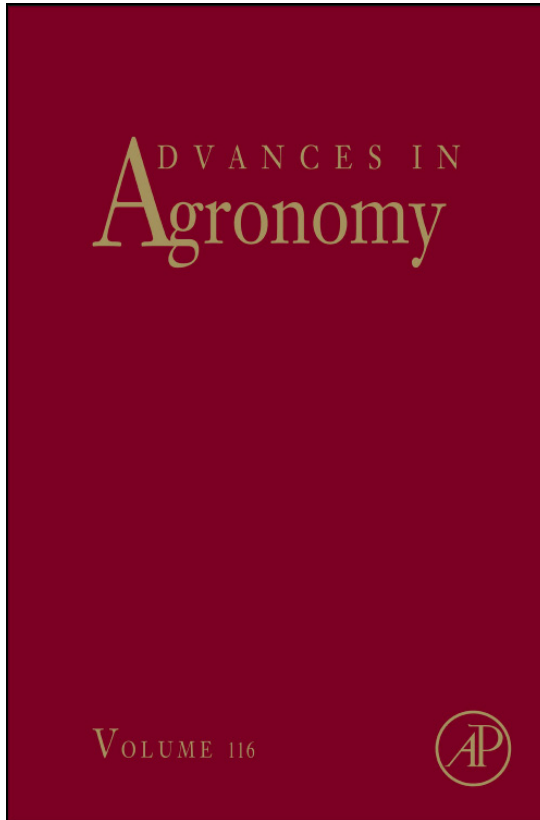


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# AGRICULTURAL PRACTICES IN OIL PALM PLANTATIONS AND THEIR IMPACT ON HYDROLOGICAL CHANGES, NUTRIENT FLUXES AND WATER QUALITY IN INDONESIA: A REVIEW

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## Abstract

Rapid expansion of oil palm (*Elaeis guineensis* Jacq.) cultivation in Southeast Asia raises environmental concerns about deforestation and greenhouse gas emissions. However, less attention was paid to the possible perturbation of hydrological functions and water quality degradation. This work aimed to review (i) the agricultural practices commonly used in oil palm plantations, which potentially impact hydrological processes and water quality and (ii) the hydrological changes and associated nutrient fluxes from plantations. Although many experimental trials provide clear recommendations for water and fertilizer management, we found that few studies investigated the agricultural practices actually followed by planters. Our review of hydrological studies in oil palm plantations showed that the main hydrological changes occurred during the first years after land clearing and seemed to dissipate with plant growth, as low nutrient losses were generally reported from plantations. However, most of those studies were carried out at the plot scale and often focus on one hydrological process at a single plantation age. So, there is insufficient information to evaluate the spatiotemporal fluctuations in nutrient losses throughout the entire lifespan of a plantation. Furthermore, few studies provided an integrated view at the watershed scale of the agricultural practices and hydrological processes that contribute to nutrient losses from oil palm plantations and the consequences for surface and groundwater quality. Future research efforts need to understand and assess the potential of oil palm plantations to change hydrological functions and related nutrient fluxes, considering agricultural practices and assessing water quality at the watershed scale.

## 1. INTRODUCTION

Oil palm (*Elaeis guineensis*) is one of the most rapidly expanding crops in the tropics. Since the early 1980s, the global land area under oil palm production has more than tripled, reaching almost 15 million ha in 2009 and accounting for almost 10% of the world's permanent crop land (FAOSTATS, 2011; Sheil *et al.*, 2009). Most of this increase has taken place in Southeast Asia. Together, Malaysia and Indonesia account for almost 85% of the 46.5 million tons of crude oil palm produced in the world, Indonesia being the top producer since 2007 (Oil World, 2011; USDA, 2007). The area covered by smallholder plantations in Indonesia increased nearly 1000-fold between 1979

and 2008, reaching almost 3 million ha, representing 39% of Indonesian oil palm plantations currently, the remaining 4.5 million ha being large private (52%) and government-owned (8%) plantations (IMA, 2010).

Although oil palm cultivation is a strong driver of economic development in Indonesia, providing jobs and incomes to millions of people (USDA, 2007), it is strongly denigrated for its environmental impacts. Many media and NGOs accuse oil palm plantation development in Southeast Asia of triggering deforestation, loss of biodiversity, peatland degradation, and high greenhouse gas (GHG) emissions (Greenpeace, 2011; WWF, 2011). In the scientific community, there is controversy about the positive and negative aspects of the expanding oil palm cultivation and potential environmental risks, which has been discussed at length in the scientific literature (Basiron, 2007; Lamade and Bouillet, 2005; Nantha and Tisdell, 2009; Sheil *et al.*, 2009). The development of oil palm plantations, which frequently cover tens of square kilometers in Southeast Asia, involves land clearing, road and drainage network construction, and sometimes earthworks such as terracing on undulating areas. The use of agrochemicals, such as fertilizers and pesticides, might represent a potential risk for the sustainability of aquatic ecosystem and hydrological functions when agricultural practices are not optimized. In particular, oil palm growers usually apply large amounts of commercial fertilizer and thus are among the largest consumers of mineral fertilizers in Southeast Asia (Hårdter and Fairhurst, 2003). However, hydrological processes within oil palm plantations are still not fully understood, and few studies have examined the impacts of agricultural practices on terrestrial hydrological functions and water quality in nearby aquatic ecosystems (Ah Tung *et al.*, 2009), although *aspects that impact on water quality are by far the largest component of an environmental risk register accounting for nearly 50% of all entries in oil palm plantations* (Lord and Clay, 2006).

This review aims to document the current state-of-knowledge of agricultural practices in oil palm plantations that potentially impact hydrological functions and water quality in surface waters, with a focus on nutrient loading of surface waterways, and to highlight research gaps in the understanding of these processes. This work focuses on the situation in Indonesia, with examples from other oil palm producing countries in the humid tropics as appropriate. First, the expansion of oil palm cultivation in Indonesia, relevant environmental issues, and polemics will be presented. Next, typical agricultural practices in industrial and smallholder oil palm plantations will be discussed, focusing on nutrient, soil, and water management. Finally, the last section gives the state-of-the-art knowledge of hydrological changes and associated nutrient fluxes from oil palm plantations compared to tropical rainforests, which were the dominant natural ecosystem prior to oil palm plantation establishment. Relevant processes in the hydrological cycle and their magnitude and relevance in oil palm plantations will be explained in this section, but we do not provide an in-depth discussion of hydrological processes in rainforests, as a number of reviews were already published on this topic (Bruijnzeel, 1991, 2004; Elsenbeer, 2001).

## 2. EXPANSION OF OIL PALM CULTIVATION IN INDONESIA AND ENVIRONMENTAL STAKES

### 2.1. Expansion of oil palm cultivation

#### 2.1.1. Palm oil utilization

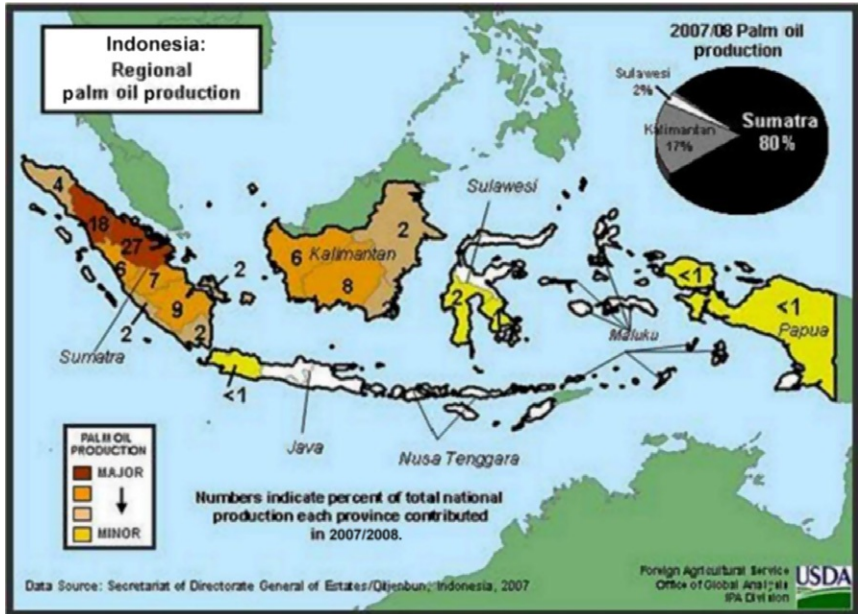
Palm oil is derived from the plant's fruit, which produces two types of oils: crude palm oil (CPO), which comes from the mesocarp of the fruit, and palm kernel oil, which comes from the seed in the fruit. Most CPO is used for food products, while most palm kernel oil is used in nonedible products such as detergents, cosmetics, plastics, as well as a broad range of other industrial and agricultural chemicals (Wahid *et al.*, 2005). The oil palm is the most productive oil crop in terms of oil yield per hectare and resource use efficiency due to its high efficiency at transforming solar energy into vegetable oil. The average yield of palm oil is approximately  $4.2 \text{ t ha}^{-1} \text{ year}^{-1}$ , with yields exceeding  $6.0 \text{ t ha}^{-1} \text{ year}^{-1}$  in the best-managed plantations, greatly exceeding vegetable oils such as rapeseed and soybean that produce only  $1.2$  and  $0.4 \text{ t ha}^{-1} \text{ year}^{-1}$ , respectively (Fairhurst and Mutert, 1999). In addition, little fossil fuel energy is used, as most of the energy required by the oil palm mill for processing of the fruits is provided by burning the palm by-products (shells and fibers). Consequently, the energy balance, expressed as the ratio of outputs to inputs, is higher for oil palm (9.6) than other commercially grown oil crops (e.g., rapeseed: 3.0; soybean: 2.5), making oil palm the most attractive candidate for biofuel production (Fairhurst and Mutert, 1999).

#### 2.1.2. Extent of oil palm cultivation in Indonesia: 1911 to present

The first commercial plantation was developed in Sumatra in 1911 and the area planted in Indonesia increased from about 31,600 ha by 1925 to 7.3 million ha by 2008 (Corley and Tinker, 2003; IMA, 2010). Since 2007, Indonesia has been the world's largest and most rapidly growing producer. Its production rose from 168,000 tons in 1967 to 22 million tons by 2010 (IMA, 2010). CPO and kernel oil prices have been rising, encouraging investors to develop plantations on the large areas of suitable land in the islands of Sumatra, Indonesia (Fig. 1) and elsewhere, mainly on the island of Borneo (USDA, 2007).

#### 2.1.3. Expected future expansion of oil palm cultivation

Continued expansion of oil palm plantations is forecast due to growing global demand for palm oil as a source of fats and oil for human consumption, nonedible products, and biofuel to keep pace with human population growth, expected to reach 8.9 billion in 2050 (Bangun, 2006; Tan *et al.*, 2009; UN, 2004). Present plans are to increase production up to 40 million



**Figure 1** Map of Indonesian palm oil production in 2007/2008 (from [USDA, 2009](#)).

tons of CPO by 2020 ([IMA, 2010](#); [Rist et al., 2010](#)). According to [USDA \(2007\)](#), the availability of land in Indonesia, coupled with other factors—high seed sales, record energy prices, and high vegetable oil prices—ensures that Indonesia will continue to lead the world in palm oil production for years to come. However, few developments generate as much controversy as the rapid expansion of oil palm in developing countries such as Indonesia ([Koh and Wilcove, 2008](#); [Nantha and Tisdell, 2009](#)). Negative consequences reported by environmental groups include deforestation, loss of biodiversity, peatland degradation, GHG emissions, and water pollution.

## 2.2. Environmental stakes

### 2.2.1. Deforestation and loss of biodiversity

The most contentious environmental issue facing the oil palm industry is deforestation as huge tracts of tropical rainforest are converted to plantations ([Germer and Sauerborn, 2008](#); [Wakker, 1999](#)). Indonesian tropical forested area ranks third behind Brazil and the Democratic Republic of Congo, and

harbors numerous endemic or rare species (Koh and Ghazoul, 2008; WRI, 2002). Many sources are claiming that virgin tropical forests are being cleared for oil palm plantations, leading to natural habitat loss for many endangered species and biodiversity reduction. For instance, it was reported that Sumatran orangutans (*Pongo abelii*) and Bornean orangutans (*Pongo pygmaeus*) face extinction due to plantation expansion (Nantha and Tisdell, 2009; Nellemann *et al.*, 2007; Tan *et al.*, 2009). Herds of elephants, tigers, and rhinos are reported to be critically threatened due to this expansion (Danielsen *et al.*, 2008; WRI, 2002). Studies in oil palm frontier areas on the island of Sumatra concluded that oil palm plantations result in a significant reduction in biodiversity if plantations replace natural forests, secondary forests, agroforests, or even degraded forests and scrubby unplanted areas (Gillison and Liswanti, 1999; Sheil *et al.*, 2009). However, others mentioned that the expansion of oil palm plantations is only one of the factors contributing to herd displacement and local extinction, as other anthropogenic activities like illegal logging, forest fires, and illegal hunting are also problematic for large mammals (Nellemann *et al.*, 2007; Tan *et al.*, 2009). According to Koh and Ghazoul (2008), at least 56% of the oil palm expansion in Indonesia during the period 1990–2005 occurred at the expense of primary, secondary, or plantation forests, and 44% was on cropland area. Deforestation in Southeast Asia cannot be attributed solely to oil palm production. According to the World Rainforest Movement (WRM, 2002), the immediate causes of rainforest destruction in Southeast Asian countries are logging by commercial companies, shifting agriculture, monoculture plantations (e.g., rubber in Thailand), cattle ranching, fuelwood harvesting, hydroelectric dams, mining and oil exploitation, and colonization schemes.

## 2.2.2. Peatland degradation

**2.2.2.1. Peatland formation** Southeast Asia has an estimated 27.1 million ha of peatlands, most of which are located in Indonesia (22.5 million ha), representing 12% of its land area (Hooijer *et al.*, 2006). Peatlands develop in depressions or wet coastal areas when the rate of biomass deposition from adapted vegetation (i.e., mangroves, swamp forest) is greater than the rate of decomposition. The accumulation of organic matter that degrades very slowly, over a period of hundreds of years, makes peat soil. This is due to the presence of a permanently high water table that prevents aerobic microorganisms from decomposing the plants debris (Mutert *et al.*, 1999; Siegel and Glaser, 2006). A soil is considered to be peat when it includes an organic layer thicker than 40–50 cm (USDA, 2006). In Southeast Asia, all low-lying peatlands are naturally forested with an average canopy height of 40 m and emergent trees of up to 50 m (WI, 2010). In the Eastern coast of the island of Sumatra, Indonesia, peat deposits are usually at least 50 cm thick but can form a deep profile that extends up to 20 m (CAAL, 2011).

**2.2.2.2. Peatland ecological functions** Peatlands regulate water flow by capturing rainwater during the wet season and slowly releasing it, over a period of months, during the dry season. Consequently, peatlands help to prevent floods and droughts (Clark *et al.*, 2002; Tan *et al.*, 2009). In addition, peatlands are an important carbon (C) sink in the global C cycle because they cover nearly 3% (some 4 million km<sup>2</sup>) of the earth's land area and store about 528,000 million tons C, which is equivalent to one-third of global soil C and 70 times annual global emissions from fossil fuel burning (Hooijer *et al.*, 2006; Tan *et al.*, 2009). Peatland attributes also include biological diversity, since tropical peatlands are important genetic reservoirs of certain animals and plants. Tropical peatlands have long-provided goods and services for local communities to fulfill their daily, basic requirements, for example, hunting grounds and fishing areas, food, medicines, and construction materials (Rieley, 2007).

**2.2.2.3. Peatland conversion to oil palm** Peat swamp forests have remained relatively undisturbed until recently, as they were unattractive for agriculture. But the increasing international demand for biofuel and the current lack of available land on mineral soils has accelerated the conversion of peatlands to oil palm plantations especially in Indonesia (Kalimantan, Sumatra, and West Papua) where nearly 25% of all oil palm plantations are located on peatlands (Sheil *et al.*, 2009; Tan *et al.*, 2009). However, oil palms cannot survive in undrained waterlogged peatlands. Drainage for oil palm growth in peatlands is installed between 40 and 80 cm depth, but the water table could recede below 80 cm during an extended drought (WI, 2010). Many authors reported that there is a direct relationship between the depth of the water table and the rate of peat subsidence and thus the sustainability of the peat (Strack and Waddington, 2007; Wösten *et al.*, 1997, 2008). Drainage results in rapid peat subsidence and compaction, leading to various changes in its physical properties including greater bulk density and less total porosity, oxygen diffusion, air capacity, available water volume, and water infiltration rate (Rieley *et al.*, 2007). Drainage ultimately destroys the "sponge effect" of peat swamps and their reservoir function (Andriess, 1988). In addition, the exploitation or removal of the overlying forest resource further reduces the ability of the ecosystem to hold rainfall, and water is flushed more quickly into the rivers, increasing flooding in the rainy season and drought in the dry season (Rieley, 2007; Rieley and Page, 1997). Moreover, the drainage of C-rich peatlands leads to aeration of the peat material and hence to the oxidation (or aerobic decomposition) of peat material resulting in massive CO<sub>2</sub> gas emissions to the atmosphere (Hooijer *et al.*, 2006; Schrevel, 2008). Although the exploitation of peat swamp forests also provides employment, local income, new jobs, and business opportunities, contributing to poverty alleviation of the country, it is at the expense of the ecosystem and the environment (Noor *et al.*, 2007).



### 2.2.3. GHG emissions and carbon storage

As mentioned in previous sections, establishment of oil palm plantations requires deforestation or peatland conversion, which irreversibly alters the GHG balance. Before 1998, most of the deforestation in Southeast Asia involved burning, which caused numerous, large, and persistent fires and consecutive GHG emissions (Tan *et al.*, 2009). In 1997–1998, these fires were particularly devastating due to a severe drought caused by the El-Niño climatic phenomenon. In Indonesia, the total area damaged or destroyed by the 1997–1998 fires was estimated at nearly 10 million ha and the overall economic cost of fire and haze in the region at \$9 billion (Glastra *et al.*, 2002). Globally, peatlands emit 2000 Mg CO<sub>2</sub> equivalents (CO<sub>2eq</sub>) year<sup>-1</sup>, equal to almost 8% of global emissions from fossil fuel burning, and more than 90% of this annual emission originates from Indonesia. Due to GHG emissions from forest burning and peatland conversion, Indonesia is in fourth place in the global CO<sub>2</sub> emission ranking (Barnett, 2007).

Nevertheless, some authors suggested that oil palm plantations may act as a C sink as they assimilate more CO<sub>2</sub> and release more oxygen (O<sub>2</sub>) than tropical forest (Lamade and Bouillet, 2005). Henson (1999) reported oil palm CO<sub>2</sub> uptake at 25.71 t ha<sup>-1</sup> year<sup>-1</sup> and O<sub>2</sub> production at 18.70 t ha<sup>-1</sup> year<sup>-1</sup> compared to 9.62 t ha<sup>-1</sup> year<sup>-1</sup> and 7.00 t ha<sup>-1</sup> year<sup>-1</sup>, respectively, in tropical forest. According to several studies reported by Henson (1999), the total dry matter production in oil palm stands was from 19.1 to 36.5 t ha<sup>-1</sup> year<sup>-1</sup>, and the total dry matter production recorded in a Malaysian forest reached 25.68 t ha<sup>-1</sup> year<sup>-1</sup>. While a new oil palm plantation may grow faster and sequester C at a higher annual rate than a naturally regenerating forest, ultimately, the oil palm plantation will store less C (50–90% less over 20 years) than the original forest cover (Germer and Sauerborn, 2008; Henson, 1999). This is due to the wide spacing between oil palm trees and control of the understory vegetation to avoid competition with the trees, whereas a natural forest has a plant community that is stratified horizontally and vertically to maximize primary production on a given acreage. Germer and Sauerborn (2008) estimated that forest conversion to oil palm causes a net release of approximately 650 Mg CO<sub>2eq</sub> ha<sup>-1</sup> on mineral soils and more than 1300 Mg CO<sub>2eq</sub> ha<sup>-1</sup> on peatlands, during the first 25-year cycle of oil palm growth (e.g., an average net release of 26 t ha<sup>-1</sup> year<sup>-1</sup> and 52 t ha<sup>-1</sup> year<sup>-1</sup> for forest and peatland conversion, respectively). However, Germer and Sauerborn (2008) also reported that if tropical grassland (instead of forest or peatlands) is converted to oil palm plantation, C fixation in plantation biomass and soil organic matter not only neutralizes emissions caused by grassland conversion but also results in the net removal of about 135 Mg CO<sub>2eq</sub> ha<sup>-1</sup> from the atmosphere.

#### 2.2.4. Water pollution

Runoff and sedimentation; leaching of nutrients from fertilizer, pesticides, and other agrochemicals; effluent discharge and sewage from the worker population, all are potential factors that could affect water quality and can be significant impacts of oil palm cultivation (ECD, 2000; Lord and Clay, 2006). The consequences of poor water quality will be borne by much of the Indonesian population: at the beginning of the twenty-first century, at least 80% of the Indonesian population (250 million) had no access to piped water, while in 2002, 66.2% of the population used river water for washing and bathing and 22.5% relied on it for drinking water (WEPA, 2011).

Runoff water can transport eroded soil particles from fields to water bodies. Suspended particles contribute significantly to water turbidity, which reduces light penetration, impairs photosynthesis, alters oxygen levels, and reduces the food supply for certain aquatic organisms (Bilotta and Brazier, 2008). Sediment clogs streams, reducing their water-holding capacity, and can cover spawning beds, destroying fish populations (Kemp *et al.*, 2011).

Mineral fertilizer application can lead to a marked increase in the nutrient concentrations of water draining from the fertilized areas (ECD, 2000). Of greatest importance for water quality are N and P exported from agroecosystems to waterways. Nitrogen is mainly applied to agroecosystems as ammonium sulfate or urea. Both ammonium compounds and urea are eventually converted into nitrate in the soil under well-drained conditions. Nitrate in water promotes undesirable growth of aquatic microflora in surface water bodies, and concentrations exceeding  $10\text{ mg NO}_3\text{ l}^{-1}$  are not recommended in drinkable water (WHO, 2008). Phosphorous in the form of orthophosphate ( $\text{PO}_4^{3-}$ ,  $\text{HPO}_4^{2-}$ , and  $\text{H}_2\text{PO}_4^-$ ) has a similar eutrophication effect in surface water as nitrate, causing excessive growth of cyanobacteria and blocking sunlight and oxygen diffusion to aquatic life in deeper water (Schindler *et al.*, 1971; Turner and Rabalais, 1994).

Pesticides, including herbicides, are commonly used in oil palm plantations, despite their adverse impacts on human beings and the environment (Sheil *et al.*, 2009). As rainfall can easily exceed  $2500\text{ mm year}^{-1}$  in Indonesia, herbicides can be washed into streams and rivers that are the only water source for all household needs—including drinking water—in villages around the plantations and contaminating fishing grounds (DE, 2005). Yet the risk of water pollution from pesticides originating from oil palm plantations is probably low, as the Malaysian Environmental Conservation Department (ECD, 2000) noted that biological control methods can be quite effective. However, to our knowledge, there has been no study on the impact of pesticide use on water quality within oil palm plantations.

Finally, palm oil production generates large amounts of waste that can pollute local waterways when disposed incorrectly. For instance, in 2001, Malaysia's production of 7 million tons of CPO generated 9.9 million tons

of solid oil wastes, palm fiber, and shells. Moreover, 10 million tons of palm oil mill effluent (POME), a polluted mix of crushed shells, water, and fat residues, was produced and often returned without treatment to natural watercourses downstream from the mill (Lord and Clay, 2006), leading to the degradation of the aquatic ecosystems (Briggs *et al.*, 2007; Sheil *et al.*, 2009). The POME is an acidic colloidal suspension characterized by high concentration of suspended solids, with a biological oxygen demand (BOD) of 25,000 ppm and a chemical oxygen demand (COD) of 60,000 ppm (Jacquemard, 1995; Olaleye and Adedeji, 2005). According to Olaleye and Adedeji (2005), riparian rivers and streams receiving untreated mill effluent are expected to be heavily polluted. Fortunately, technologies have been developed to treat and reclaim drinking water from the POME (Ahmad *et al.*, 2006; Rupani *et al.*, 2010; Singh *et al.*, 2010; Yi Jing *et al.*, 2010), and they need to be widely implemented to protect downstream waters. Sewage from the worker population in the plantation is another waste byproduct that is expected to elevate COD, BOD, and fecal coliform levels in waterways.

### 2.2.5. Agricultural policies

The pressing environmental and social issues associated with the palm oil industry were the impetus for dialog between palm oil stakeholders and NGO representatives regarding methods to achieve sustainable palm oil production and use, including better management practices (BMP) for agronomists and planters working with this industry (Darussamin, 2004). Thus, the Roundtable on Sustainable Palm Oil (RSPO), an international organization of producers, distributors, environmental NGOs, and social NGOs, was created and defines sustainable palm oil production as *a legal, economically viable, environmentally appropriate, and socially beneficial management and operations* (Tan *et al.*, 2009). RSPO has recently established a set of principles and criteria for the management of oil palm plantations and palm oil mills and encourages the planters to follow BMP (Lord and Clay, 2006). These practices are environment-friendly approaches like zero burning for land clearing, conservation of wildlife and habitat, integrated pest management (IPM), and waste minimization and recycling. For example, IPM in plantations relies on barn owls or snakes to reduce rat populations instead of pesticides (Hansen, 2007; Sheil *et al.*, 2009). Planting leguminous cover crops (LCC) to minimize soil erosion and maintain soil fertility and the recycling of palm oil empty fruit bunches (EFB) and POME as fertilizer in the plantation are also promoted. These environment-friendly practices could reduce the use of mineral fertilizers (Tan *et al.*, 2009) and improve water quality.

The Indonesian government also has recently started to encourage planters to improve the sustainability of their plantations. The Indonesian Sustainable Palm Oil (ISPO) was launched in 2010 by the government of Indonesia and will be compulsory in the coming years for all oil palm growers, while RSPO is still a voluntary process. In addition, Indonesia

government has recently edited a guideline on oil palm cultivation on peatland “to manage the peatland in a sustainable way considering the ecological function of peatland.” It stipulates, among other things, that the land clearing will be done without burning (since 1998, zero burning is compulsory in Indonesia) and an intensive and quick process of drying is not allowed, to avoid irreversible shrinkage. The decree also lays down that oil palm cultivation on peatland must be restricted to (a) areas in which the peat extended less than 3m below the surface; (b) areas where the subsoil under the peatland is not silica sand or acid sulfate soil to avoid the toxic effects of the oxidation of the pyrite and accumulation of sulfuric acid, due to the drop in water table level (Zaidel'man, 2008); (c) areas with mature peat soils, classified as sapric (the most decomposed) or hemic (somewhat decomposed); and (d) areas with eutrophic peatlands (Ministerial Decree on Agriculture, 2009).

### 2.2.6. Implications for future research

To date, most of the attention and research related to the environmental impact of oil palm cultivation has focused on deforestation and its consequences (loss of biodiversity, GHG emissions from burning, etc.) during the initial phase of oil palm plantation establishment. Much less attention has been paid to the environmental impacts of established oil palm plantations, particularly hydrological changes and water pollution. Understanding and assessing the activities in oil palm plantations that impact hydrological functions and associated nutrient fluxes requires a good knowledge of all agricultural practices followed throughout the entire life cycle of the plantation. In the next section, we describe the preferred growing conditions for oil palm (climate, soils) and agronomic considerations (site preparation, tree spacing), with emphasis on nutrient, soil, and water management in different production systems (industrial and smallholders).

## 3. OIL PALM CULTIVATION

### 3.1. Climate and soil conditions

The African oil palm (*Elaeis guineensis*, family Arecaceae) is a tropical forest palm native to West and Central African forests. Oil palm needs humid equatorial conditions (1780–2280mm annual rainfall and a temperature range of 24–30°C) to thrive, and so conditions in Southeast Asia are ideal (Corley and Tinker, 2003). Palm productivity benefits from direct sunshine: the lower incidence of cloud cover over much of Southeast Asia is thought to be one reason why oil palm yields are higher there than in West Africa (Dufrière *et al.*, 1990). Oil palm is tolerant of a wide range of soil types, as long as it is well watered. Seasonal droughts at higher tropical latitudes

greatly reduce yields (Basiron, 2007). The oil palm is cultivated predominantly on tropical soils in the orders Ultisol, Oxisol, and Inceptisol. These soils are highly acidic with low buffering capacities (Ng, 2002) as a consequence of cation leaching (Caliman *et al.*, 1987). Once the pH drops below 5.5, aluminum and manganese compounds start to dissolve, which may cause root deterioration (Godbold *et al.*, 1988). However, oil palm is adapted to acidic conditions (Omoti *et al.*, 1983), and with appropriate management, oil palm plantations can also be productive on “problem soils” such as acid sulfate soils, deep peat and acidic high aluminum soils, where few other crops are successful (Corley and Tinker, 2003).

### 3.2. Production systems: Industrial versus smallholder plantations

Oil palm-growing areas in Indonesia are distributed among three production systems: government holdings, private companies, and smallholders. In 2010, the Indonesian Ministry of Agriculture estimated that of almost 8 million ha under oil palm cultivation, private companies held 53%, smallholders had 39%, and the remaining 8% belonged to government plantations. Private and governmental estates typically range in size from 3000 to 20,000 ha (Sheil *et al.*, 2009), while the smallholders are defined as family-based enterprises producing palm oil from less than 50 ha of land, often about 2 ha (Vermeulen and Goad, 2006). When the price of palm oil in the international market was exceptionally high (around US\$ 700 per ton in 1974), efforts were made to increase production. The government established a strategy called the nucleus estate scheme (NES), where state-owned or private plantation companies (*nucleus*) helped smallholder farmers to grow oil palm on 2–3 ha of land in the surrounding area (*plasma*) (Bangun, 2006; IEG, 1993; Zen *et al.*, 2005). Smallholders working under contract to the plantation companies received seedlings of high-yielding cultivars, technical assistance for land preparation and planting, agrochemical inputs (fertilizers and pesticides), management assistance, and loan access (Bangun, 2006; Vermeulen and Goad, 2006). The estates benefited through their fees for services and return from milling smallholder fruit into CPO (Zen *et al.*, 2005). In contrast to smallholders working under the NES, independent smallholders cultivate oil palm without direct assistance from government or private companies. They sell their crop to local mills directly or through buyers (Vermeulen and Goad, 2006).

### 3.3. Land clearing and site preparation

Many authors provide recommendations for the establishment of an oil palm plantation including land clearing, road and drainage network construction, caring for pre-nursery and nursery stages, planting, and management of immature and mature trees until replanting. Among the most

popular agronomic handbooks for oil palm cultivation are [Corley and Tinker \(2003\)](#), [Jacquemard \(1995\)](#), [Rankine and Fairhurst \(1998a,b,c\)](#), and [Hartley \(1988\)](#).

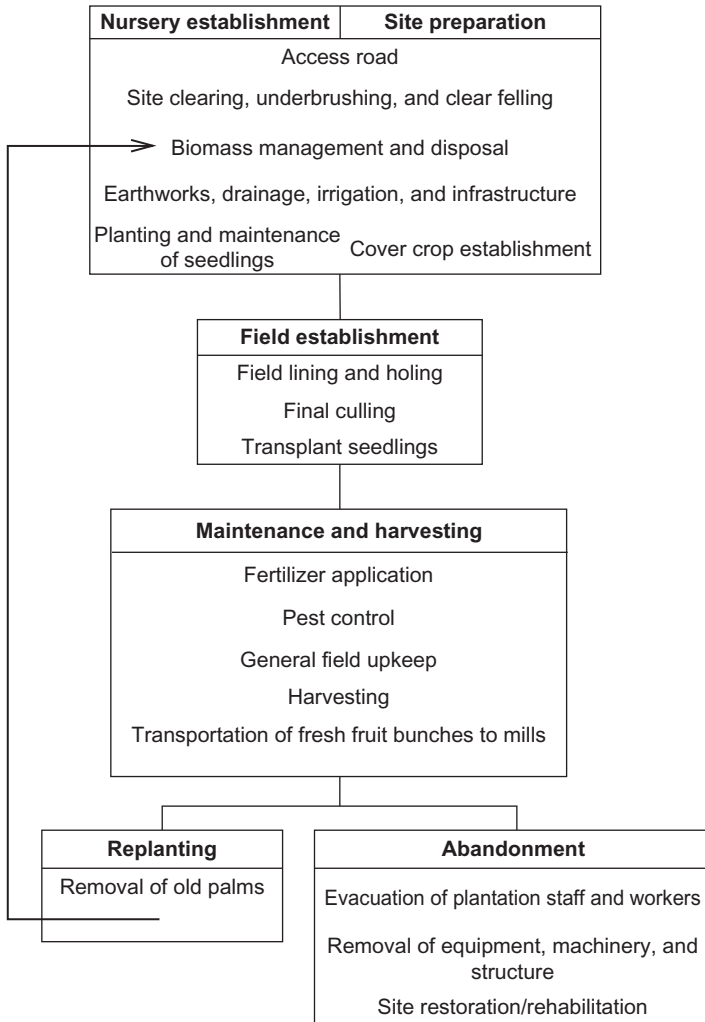
Once the site is selected, establishment of the oil palm plantation starts with land clearing. At present, mechanical methods are used in all major oil palm-growing countries with chainsaws, winches, and bulldozers. Then, the felled vegetation is either burnt or allowed to rot. The issue of whether or not to burn the felled vegetation has remained a subject of controversy for years ([Corley and Tinker, 2003](#)) due to environmental impacts of burning: smoke, haze, and large nutrient losses through volatilization and ash carried away ([Mackensen \*et al.\*, 1996](#)). Since the massive fires in Kalimantan and Sumatra in 1997, the Indonesian government prohibited burning ([Corley and Tinker, 2003](#)). However, according to some media, laws to limit agricultural burning are poorly enforced and burning still continues ([Mongabay Editorial, 2006](#)).

The general layout of a plantation is decided by the topography, the drainage, the position of the mill, and the distance to transport fresh fruit bunches (FFB) to the nearest road. [Hartley \(1988\)](#) recommends a gap of 320 m between roads, giving a density of 33 m roads ha<sup>-1</sup>, that is, 3% of the land area. In hilly areas, the road density should increase, with distances between roads not exceeding 200 m, due to the difficulty of transporting FFB across platforms and terraces. With terraces, the distance should be 125 m, the density being 80 m roads ha<sup>-1</sup>. A typical road layout in hilly estates has to be arranged in relation to the drainage lines and streams. If the roads can run parallel to streams, this reduces the number of bridges needed and helps to avoid crossing over swampy areas ([Corley and Tinker, 2003](#)). Steps for the establishment and exploitation of an oil palm plantation on a typical private estate are summarized in [Fig. 2](#).

### 3.4. Water and soil management

Water management is a crucial aspect of oil palm cultivation as deficit or excess of water stresses oil palm trees and is highly detrimental for crop yields. Water management mainly aims at minimizing impacts of drought and floods and optimizing the use of rainwater and fresh water from streams by drainage, irrigation, and soil moisture conservation practices. [Corley and Tinker \(2003\)](#) provided detailed information on irrigation in oil palm plantations. In Indonesia, rainfall is generally well distributed over the year, so irrigation is not common in oil palm plantations, except in South Sumatra where yield-limiting water deficits may occur during the dry season.

Drainage systems are common in Indonesian oil palm plantations, particularly in flat areas with a high water table where drainage is compulsory to remove excess water and promote oil palm root proliferation in deeper soil layers. Indeed, optimum depth of water table for oil palm growth is 50–75 cm



**Figure 2** Typical oil palm plantation development activities (adapted from [ECD, 2000](#)).

([APOC, 2011](#); [Goh and Chew, 1995](#)). To achieve this, a good outlet with sufficient capacity to discharge excess water is needed ([Corley and Tinker, 2003](#)). Another possibility is to install controlled drainage systems that retain subsurface water in the drains prior to dry periods. Generally, the drainage system consists of an interconnected network of collection and main drains of varying dimensions depending on the hydrological and rainfall characteristics of the area ([Othman \*et al.\*, 2010](#)). The slope, intensity, and dimension of

drains depend largely on the expected amount of water to be removed during wet periods. To achieve the desired water level, the minimum drain intensity is at least one drain for every eight rows of palm and the intensity could be further increased to one in every four or even to one in every two rows of palms. Higher drainage intensity is adopted on clayey soils than sandy soils, which naturally have better drainage (Goh and Chew, 1995).

Water management is more critical on undulating, hilly, or inland soils because growers need to maintain soil moisture and minimize soil erosion and nutrient losses. The American Palm Oil Council (APOC) recommends (1) digging of silt-pits and foothill drains to trap water sediments from surface runoff; (2) stacking fronds across the slope to minimize the velocity of water runoff downhill slopes and to conserve water through mulching; and (3) planting LCC, which not only helps replenish soil organic matter stock but also reduces the velocity of soil and water movement. The LCC commonly established in oil palm estates include *Mucuna bracteata*, *Pueraria phasesloides*, and *Calopogonium ceeruleum*. In steep terraced areas, deep rooting *Vetiver* grass can be used to prevent soil erosion and regulate water excess.

However, water management and soil conservation are not practiced by all planters. Plasma smallholders may benefit of drainage network implemented by large companies involved in the nucleus-plasma scheme, whereas independent smallholders may not have the financial and technical means to dig and maintain a drainage network within their plantations, nor knowledge of soil moisture and soil conservation practices. Despite abundant literature and recommendations for water management, studies investigating actual and current water management practices in oil palm plantations, especially in smallholdings, are almost nonexistent.

### 3.5. Nutrient-demand assessment

Despite the absence of mineral elements in the palm oil, large quantities of nutrients are required by the palm tree to support its vegetative growth and fruit production, which cannot be provided by inland and upland soils in Sumatra and Borneo due to their low fertility status (Goh and Hårdter, 2003). Thus, mineral fertilizers are compulsory to supplement the low indigenous soil nutrient supply and to ensure suitable yields. Fertilizers account for 50–70% of field operational costs and about 25% of the total cost of production (Caliman *et al.*, 2007; Goh and Hårdter, 2003). Understanding the factors that contribute to efficient fertilizer use is crucial to maximize yields and enhance economic returns (Goh and Hårdter, 2003). Consequently, the Indonesian oil palm industry has invested millions of dollars in research and development to improve fertilizer use. Many trials have been conducted on a wide range of soil types, climate, and tree ages in order (i) to determine the ecophysiological nutrient demand of oil palm for



targeted yields (Tarmizi and Mohd, 2006); (ii) to determine input levels to achieve an economically optimum production (income vs. costs of production) (Breure, 2003; Caliman, 2001; Caliman *et al.*, 1994; Goh and Hårdter, 2003) including recommended types, rates, and timing of fertilizer applications to minimize nutrient losses (Goh and Chew, 1995); and also (iii) to develop agricultural practices aiming at minimizing chemical fertilizers inputs such as the establishment of a LCC during the immature stage (Agamuthu and Broughton, 1985), recycling of pruned fronds and male inflorescences (Ng and Thamboo, 1967), mulching of EFB (Caliman *et al.*, 2001; Chiew and Rahman, 2002; Loong *et al.*, 1987), and POME spreading (Rupani *et al.*, 2010; Wood *et al.*, 1979). These studies led to an abundant literature on recommendations for optimum nutrient management in oil palm plantations (Corley and Tinker, 2003; Fairhurst *et al.*, 2005; Kee and Goh, 2006).

Fertilizer management in oil palm plantations is based on nutrient balance principle, which estimates the total demand of the palm and matches it with the nutrient supply in the oil palm plantation and from supplemental fertilizers (Goh *et al.*, 1999). Nutrient demand can be divided in two categories: nutrient uptake and nutrient losses from soil through processes such as runoff, leaching, and gaseous emissions. Within nutrient uptake, we distinguish nutrient stocks exported by harvesting (FFB) and nutrients immobilized in the palm biomass (for growth) (Goh, 2004; Goh and Hårdter, 2003). Some authors also calculate nutrients recycled from pruned fronds and male inflorescences because they are usually returned to the soil (Tarmizi and Mohd, 2006). The nutrient requirements of oil palm vary widely, depending on the target yield, genetic potential of the planting material used, and numerous environmental factors such as tree spacing, palm age, soil fertility, groundcover conditions, and climate (Fairhurst and Mutert, 1999; Goh and Hårdter, 2003; Tarmizi and Mohd, 2006). Table 1 compares the total nutrient stocks in standing biomass of oil palm plantation and tropical forest, illustrating that 1 ha of forest generally contains more nutrients in plant biomass than a plantation. Table 2 shows nutrient uptake and allocation for production, immobilization in palm biomass, and recycling, based on data from trials in Southeast Asia. Generally, a larger proportion of nutrient uptake is needed for FFB than for immobilization. For example, Ng *et al.* (1999) reported, for a target yield of  $25 \text{ t ha}^{-1} \text{ year}^{-1}$ , the annual nutrient uptake in FFB was 2.3-fold greater than nutrients immobilized in new biomass.

The soil nutrient supply in an oil palm plantation comes from dissolved nutrients in atmospheric deposition, including precipitation, nutrients recycled from pruned fronds and male inflorescences when these are returned to the soil, nutrients leached by rainfall from the leaf canopy (leaf wash), nutrient returns from LCC, available nutrients present in the soil, and fertilizer applications (Goh, 2004; Goh and Hårdter, 2003; Goh *et al.*, 1999;

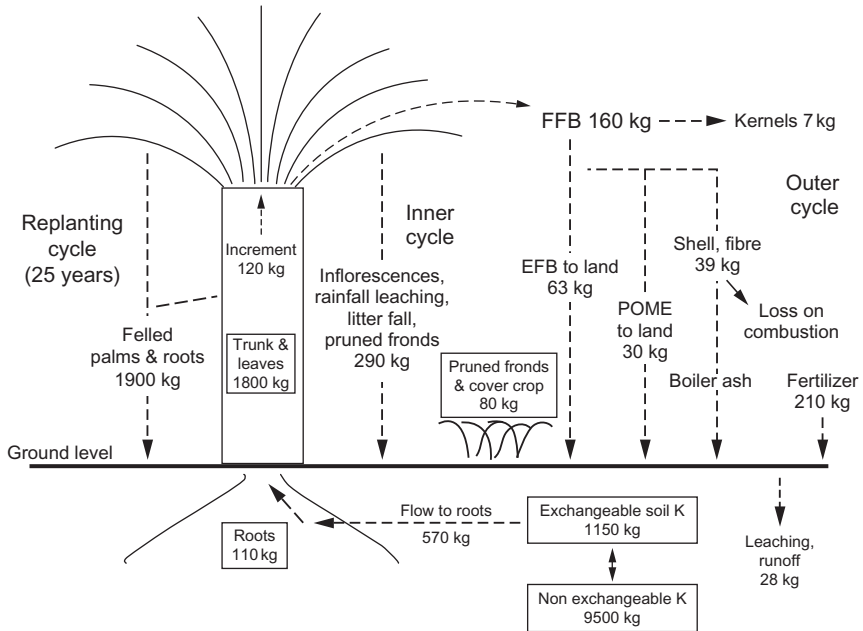
**Table 1** Standing stock biomass in oil palm plantation and topical forest (adapted from [Henson, 1999](#))

Vegetal cover	Mean biomass	Total stocks in standing biomass (kg ha <sup>-1</sup> )					Source
		N	P	K	Mg	Ca	
Oil palm, 14 years	94 t ha <sup>-1</sup> for 136 palms ha <sup>-1</sup>	588	58	1112	151	173	<a href="#">Ng <i>et al.</i> (1968)</a>
Rainforest (5 studies range)	385 t ha <sup>-1</sup>	1067–2980	33–315	340–3163	161–595	476–4168	<a href="#">Anderson and Spencer (1991)</a>

**Table 2** Nutrient uptake in different components of oil palm plantations

Oil palm components	Target yield (ton FFB ha <sup>-1</sup> yr <sup>-1</sup> )	Nutrient contents in oil palm biomass (kg ha <sup>-1</sup> yr <sup>-1</sup> )					Source
		N	P	K	Mg	Ca	
<i>Production</i>							
Harvested fruit bunches	24	72.5	12.1	93.2	20.7	–	Ng and Thamboo (1967), Ng <i>et al.</i> (1968)
	25	73.2	11.6	93.4	20.8	19.5	Ng <i>et al.</i> (1968)
	30	97.6	10.0	105.4	18.2	–	Tarmizi and Mohd (2006)
	30	99.1	15.6	129.3	33.3	–	Ng <i>et al.</i> (1999)
<i>Immobilized</i>							
Trunk	30	42.4	4.1	121.6	10.2	–	Ng <i>et al.</i> (1999)
Roots	–	16.6	1.1	2.8	0.42	–	Corley <i>et al.</i> (1971)
Trunk & roots	30	18.5	2.4	61.9	3.8	–	Tarmizi and Mohd (2006)
Immobilized in new biomass	25	40.0	3.1	55.7	11.5	13.8	Ng <i>et al.</i> (1968)
<i>Recycled</i>							
Pruned fronds and male inflorescences	24	78.4	11.3	102.1	28.1	–	Ng and Thamboo (1967), Ng <i>et al.</i> (1968)

FFB, Fresh Fruit Bunch.



**Figure 3** Total demands and sinks for potassium in an oil palm plantation with 30 ton FFB yield (from Corley and Tinker, 2003). EFB, empty fruit bunch; FFB, fresh fruit bunch; POME, palm oil mill effluent.

Tarmizi and Mohd, 2006). As an example, the potassium fluxes in oil palm plantation are illustrated in Fig. 3.

Some research groups developed complex models, based on the nutrient balance principle, to assess nutrient requirements, taking account of the commodity price and fertilizer cost. Corley and Tinker (2003) reported on three of these models, which are summarized below:

1. The Applied Agriculture Research group in Malaysia developed a linked group of models for oil palm management, which include a model to assess site-specific yield potential (ASYP), a model for predicting the fertilizer requirements, the integrated site-specific fertilizer recommendation system (INFERS), and expert systems for determining best month for fertilizer application, and the timing and allocation of different fertilizers (Kee *et al.*, 1994; Kok *et al.*, 2000).
2. Leaf analysis is the most common diagnostic tool to determine the nutritional status of oil palm and estimate the appropriate fertilizer rates because of significant relationship between leaf nutrient concentration and FFB yield (Foster and Chang, 1997; Goh, 2004). It is largely used by the International Cooperation Centre in Agronomic Research for

Development (CIRAD), which carries out leaf analysis of palms located on important soil types within the plantation and uses response curves of the leaf analysis results to determine the critical level corresponding to the economically optimal fertilizer rate (Caliman *et al.*, 1994, 2001).

3. The Foster system (PORIM fertilizer recommendation system) involves two basic approaches: (i) the use of site-specific characteristics to determine yield without fertilizer, fertilizer need, and the efficiency of response to fertilizer (Foster, 1995; Foster *et al.*, 1986) and (ii) leaf analysis data (Foster and Chang, 1977; Foster *et al.*, 1988).

### 3.6. Fertilizer management

#### 3.6.1. Chemical fertilizer

The dominant fertilizers produced and used in Indonesia are urea (46% N); triple superphosphate (TSP, 46% P<sub>2</sub>O<sub>5</sub>); rock phosphates (RP, 27–34% P<sub>2</sub>O<sub>5</sub>); ammonium sulfate (AS, 21% N and 24% S); potassium chloride, also called muriate of potash (KCl or MOP, 60% K<sub>2</sub>O); magnesium sulfate, also called kieserite (17% Mg, 23% S); and blended NPK, NP, and PK fertilizers (FAO, 2005). Table 3 shows some recommended fertilizer application rates, which vary according to climatic conditions, soil type, age of palms, and palm yield potential. The optimal frequency of fertilizer application depends on crop requirements, tree age, ground conditions, types of fertilizer available, and rainfall. For example, frequent application of fertilizer at low rates is preferred for sandy or sloped land where the risk of nutrient losses through runoff or drainage is great. In such areas, a single annual application of water-insoluble rock phosphate is recommended, whereas soluble fertilizers would be applied in low doses several times a year. More frequent fertilizer application is also advised for immature trees (Goh and Chew, 1995). Some authors recommend fertilizer applications close to the tree base in the initial years, and to be gradually extended to the tree avenues when the canopy overlaps and good root development is reached (Goh and Chew, 1995; Goh *et al.*, 2003). Moreover, the timing of fertilizer application should account for the rainfall pattern to avoid substantial nutrient losses (Goh and Chew, 1995; Goh *et al.*, 2003). Thus, the general guideline is to avoid fertilizer applications during period with high rainfall, such as during months with more than 250mm month<sup>-1</sup>, months with high rainfall on more than 16 days month<sup>-1</sup>, and months with high-intensity rainfall events of more than 25mm day<sup>-1</sup> (Goh and Chew, 1995).

#### 3.6.2. Organic fertilizer

The value of oil palm residues such as pruned fronds and other wastes from processing mills for mulch and organic manure is well documented (Dolmat *et al.*, 1987; Khalid *et al.*, 2000; Loong *et al.*, 1987). According to Fairhurst

**Table 3** Recommended fertilizer applications for oil palm in South East Asia

Fertilizer applications ( $\text{kg ha}^{-1} \text{ year}^{-1a}$ )										
Notes	N	Notes	P	Notes	K	Notes	Mg	Notes	B	Source
Immature	45	Immature	24	Immature	108	Immature	28	Immature	0.6	FAO (2005)
Mature	120	Mature	22	Mature	286	Mature	24	Mature	0.6	
Immature	35–105	Coastal clay soil	42–56	Depending on site	42–420	Mg sufficiency	8.4–35	Immature	1.4	Goh <i>et al.</i> (2003)
Mature	35–245	Malaysian inland soils	56–98	conditions		Mg deficiency	42–105	Mature	2.1–4.9	Goh <i>et al.</i> (2003)
Immature	50–120	Immature	22–48	Immature	54–216	Immature	7–24	Immature	1.2–3.7	von Uexküll (2007)
Mature	120–200	Mature	30–87	Mature	183–581	Mature	0–36	Mature	2.5–5.6	von Uexküll (2007)

<sup>a</sup> Assuming 140 palms  $\text{ha}^{-1}$  when recommendations were expressed as  $\text{kg palm}^{-1}$ .

(1996), field palms yielding 30t FFBha<sup>-1</sup> in West Sumatra return to the soil about 10tha<sup>-1</sup>year<sup>-1</sup> dry matter from pruned fronds, which contain 125kg N, 10kg P, 147kg K, and 15kg Mg. Also, both EFB and POME contain substantial amounts of nutrients and organic matter that can replenish the soil fertility and help meet the nutrient requirements for oil palm. According to Tailleux (1998), mulched EFB can reduce the need for chemical fertilizers by more than 50% in immature stands and by 5% in mature stands. Application of 40–60t EFBha<sup>-1</sup>year<sup>-1</sup> or 750m<sup>3</sup> POMEha<sup>-1</sup>year<sup>-1</sup> is recommended to add organic matter and improve soil fertility on poor inland soils (Goh *et al.*, 1999).

### 3.7. Synthesis

Industrial and smallholder planters do not have the same resources to ensure optimum nutrient management. Specifically, independent smallholders do not benefit from techniques such as leaf diagnosis and soil analysis (Fairhurst and Mutert, 1999; Pushparajah, 1994) to assess the nutrient requirements of their plantations. In many smallholdings, low-productivity palms are planted unevenly without terracing, and fertilizer use is inadequate and unbalanced (urea applied alone) (FAO, 2005; Webb *et al.*, 2011; Zen *et al.*, 2005). Some smallholders observe and copy the industrial plantations in recycling pruned fronds and male inflorescences, but not all. Moreover, they do not benefit from organic inputs of EFB and POME, which are available only in industrial or governmental estates where the mills are located. Unfortunately, few data are available on actual fertilization practices in most oil palm plantations in Indonesia. Some authors provide estimates of average yields of palm oil from the different management groups, which are generally higher for private plantations than smallholdings, although the FAO estimated similar yields for these two groups (Table 4). However, these estimates should be interpreted with caution as they do not account for the high variability for cultural practices among planters. Although some

**Table 4** Average yields of palm oil production for the different production systems in Indonesia (tha<sup>-1</sup>)

Smallholder	Industrial		Source
	Government	Private	
1.8	3.7	1.7	FAO (2005) (in 2002)
3.3 (5)	4.2 (7)	4.1 (7)	USDA (2009) (in 2008)
2.34		3.04–5.52	Bangun (2006)

( ), potential yields.

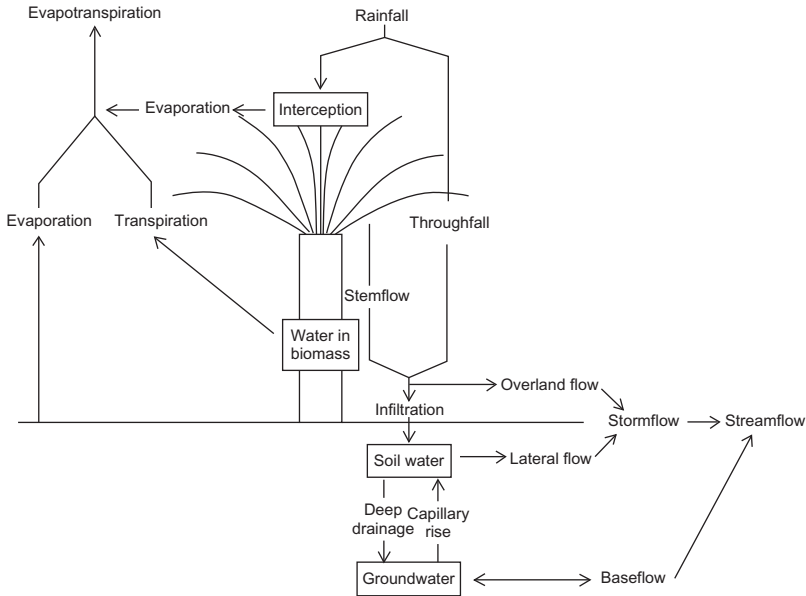
private producers have recorded high yields of 6.5–8.0  $\text{tha}^{-1}$  on individual plantations, the gap between yields on smallholdings and private estates is inexplicably low, given the tremendous advantages that private estates show in capital, land management abilities, fertilizer availability, and access to high-yielding varieties (USDA, 2009). Two possibilities to explain this discrepancy are (1) producers on private estates have seriously underinvested in soil fertility and fertilizer use efficiency, as they have the financial resources to manage nutrients for higher yields, or (2) producers on private estates have not been motivated to manage their trees intensively, as they already achieve sufficient profit margins (USDA, 2009).

Abundant recommendations exist for soil, water, and nutrient management on oil palm plantations, especially for large plantations, but smallholder farms are generally not large enough for trials to be implemented (Webb *et al.*, 2011). Moreover, there is scant or no data available from study cases on the actual management practices and fertilizer use in industrial plantations, let alone smallholdings. However, these practices have a high potential to impact hydrological processes and associated nutrient fluxes from oil palm plantations.

#### **4. HYDROLOGICAL PROCESSES AND ASSOCIATED NUTRIENT TRANSFERS IN OIL PALM PLANTATIONS**

Replacing a natural forest with an oil palm plantation is expected to *drastically* change the existing characteristics of the area and to modify the hydrological cycle, shown in Fig. 4 (Henson, 1999). The activities related to the oil palm plantation establishment and exploitation (e.g., complete clearing of forested areas, construction of roads and drainage networks, fertilizer and agrochemical use, wastewaters release from mill and worker residences) are expected to cause problems related to water flow (e.g., flooding incidents downstream) and increase nutrient and sediment delivery to streams, causing deterioration in water quality (ECD, 2000; Goh *et al.*, 2003). This section aims to (1) compare hydrological processes in naturally forested watersheds with those under oil palm plantation, including the hydrological changes occurring during oil palm development (immature vs. mature plantations) and (2) highlight gaps in literature regarding the understanding of hydrological processes in oil palm plantations and the consequences for water quality. We do not review hydrological processes in tropical forests as a number of detailed reviews were already published (Bruijnzeel, 1990, 2004; Douglas, 1999; Elsenbeer, 2001), but will refer to those data to illustrate the magnitude of change in hydrological processes occurring in oil palm plantations.





**Figure 4** The hydrological cycle in an oil palm plantation. Boxes indicate storage pools, arrows indicate fluxes.

#### 4.1. Precipitation in Indonesia

Indonesia's humid tropical climate is characterized by seasonal changes in rainfall largely determined by monsoons winds, due to its location in the equatorial zone, between the Asian and Australian landmasses. Typically, the northwest monsoon brings rain from December through March, followed by the southeast monsoon, which brings drier weather from June through September (Galdikas, 2009). Rainfall patterns in Indonesia vary from one region to another (Aldrian and Dwi Susanto, 2003). Annual rainfall in lowland areas is between 1800 and 3200mm, increasing with altitude to an average of 6100mm in some mountainous regions. In the lowlands of Sumatra and Kalimantan, the annual rainfall averages 3000–3700mm.

#### 4.2. Interception

Studies of hydrological processes in tropical rainforests indicate the importance of interception by the leaves and branches (canopy) of plants. In his review, Bruijnzeel (1990) concluded that forest interception was between 4.5% and 22% of the rainfall incident on the canopy, with an average value of 13%. Compared to natural forest vegetation, a lower proportion of rainfall is expected to be intercepted by palms as a result of lower leaf area

index, even in mature oil palm plantations (Henson, 1999) due to clearing of most understory vegetation. Dufrêne (1989) reported that less than 5% rainfall was intercepted following a 30-mm precipitation event and lower values were recorded at higher rainfall intensity. However, Squire (1984) found that interception was 17–22% of precipitation in oil palm plantation, the amount varying with palm age, erectness of canopy, and rainfall intensity.

In tropical forests, only a small amount of rain falls directly on the ground or into water bodies, as most of the rainfall will reach the soil via throughfall and stemflow, which are responsible for transferring nutrients from the canopy to the soil. Some Malaysian studies found that throughfall transferred 70–78% of rainfall in mature oil palm plantations (Kee *et al.*, 2000). In Papua New Guinea where rainfall is higher, Banabas *et al.* (2008) found that 83% of the rain reached the ground as throughfall. These values are the same order of magnitude as those reported by Bruijnzeel (1990) for lowland rainforest: 77–93% of incident rainfall (on average 85%) was transported by throughfall. We are not aware of published data on throughfall, stemflow, and rainfall interception by immature oil palm when the canopy has not yet closed.

### 4.3. Evapotranspiration

A number of evapotranspiration (ET) studies were carried out in tropical forests (Noguchi *et al.*, 2004; Tanaka *et al.*, 2008; Zulkifli *et al.*, 1998). In three catchments in Selangor, Malaysia with more than 94% forest cover, Low and Goh (1972) found ET accounted for half of the 2162–2482mm annual rainfall when estimated as the difference between measured rainfall and water outflow from the catchment. In a study in the Sungai Tekam Experimental Basin, Malaysia (DID, 1989) that received average annual rainfall of 1878mm for the period 1977/1978 to 1985/1986, the actual ET of a forested catchment averaged  $1500\text{mm year}^{-1}$  (range: 1374–1583mm year<sup>-1</sup>), which represents 99% of the potential ET, on average  $1515\text{mm year}^{-1}$  (range: 1449–1567mm year<sup>-1</sup>) based on the Penman & Thornwaite method of estimation. In his review, Bruijnzeel (2004) reported ET typically ranged from 1000 to 1800mm year<sup>-1</sup> in lowland and hill *dipterocarp* forests in Peninsular Malaysia.

There have been few ET studies in oil palm plantations (Yusop *et al.*, 2008). Micrometeorological measurements in mature oil palm on a Malaysian coastal site showed that ET accounted for 83% of rainfall and was close to potential ET calculated by the Penman equation (Henson, 1999). A study of oil palm on volcanic soils in Papua New Guinea gave an estimated ET of 1334–1362mm year<sup>-1</sup>; Banabas *et al.* (2008) noted that water deficit was unlikely to limit transpiration in this area, which had average annual rainfall between 2398 and 3657mm. Radersma and de Ridder (1996) estimated oil

palm ET of 1018–1051 mm year<sup>-1</sup> from literature data. We know of one published report on ET in immature oil palm plantations. Yusop *et al.* (2008) estimated ET in three catchments where oil palm ages ranging from 2 to 9 years, using short-time period water budget and catchment water balance. Surprisingly, they found higher values (1405 and 1365 mm year<sup>-1</sup> for the two methods, respectively) in the 2-year-old plantation than the 9-year-old plantation (927 and 1098 mm year<sup>-1</sup>, respectively), as higher transpiration is expected in mature plantation. They concluded that ET values in the older plantation were underestimated. Overall, these literature reports suggest high ET in mature oil palm plantations in Southeast Asia, ranging from about 1000–1300 mm year<sup>-1</sup>, which is similar to ET in tropical rainforests. However, few studies report ET in immature oil palm plantation, and the difference in ET of different age plantations remains to be fully investigated.

#### 4.4. Soil infiltration, leaching, and groundwater quality

##### 4.4.1. Soil infiltration

Water reaching the ground may either infiltrate into the soil or flow directly to the stream through surface runoff. Partitioning between surface runoff and infiltrated water essentially depends on soil infiltrability and rainfall intensity. Once infiltrated, water can either percolate downward as vertical flow or reach the stream through lateral (downslope) subsurface flow, depending on soil hydraulic conductivity gradient. In rainforests, water moves within the soil as matrix flows or more rapidly through bypass or preferential flows (roots channels, macropores) in both vertical and lateral directions (Noguchi *et al.*, 1997a). It is well known that soil infiltration capacity depends on soil texture (FAO, 1990) and on land use (Chorley *et al.*, 1984; Osuji *et al.*, 2010). Many studies showed that tropical forest soils have high infiltration capacities (Bruijnzeel, 1990), due to dense vegetation (increases water uptake and ET from the system) and high soil organic matter content that improves the soil structure and enhances its porosity. For example, high infiltration rates of 200–250 mm h<sup>-1</sup> were found in two tropical forest soils of western Nigeria under bush fallow (natural regrowth) (Wilkinson and Aina, 1976). According to Bruijnzeel (2004), about 80–95% of incident rainfall infiltrates the soil in a mature tropical rainforest. However, some studies showed that hydraulic conductivities decrease rapidly with soil depth in forested land, leading to shallow subsurface flow from the nearly saturated topsoil and contributing to stormflow generation (Bidin *et al.*, 1993; Malmer, 1996; Noguchi *et al.*, 1997b). This phenomenon was also observed by Yusop *et al.* (2006) in forested catchments in Malaysia due to positive hydraulic pressure at 10 cm depth during storms, despite high hydraulic conductivity (169–1485 mm h<sup>-1</sup>).

Deforestation can affect infiltration capacity of soils in a number of ways. According to DID (1989), removal of forest reduces transpiration and

increases soil moisture storage, which resulted in soils reaching field capacity earlier during rainfall events. Infiltration rates will also be reduced immediately following deforestation when soils are compacted by heavy machinery. However, DID (1989) showed that infiltration rates return to predisturbance levels following the establishment of crops due to improvement in soil structure under vegetative ground cover.

According to Banabas (2007), soils under mature oil palm typically have high infiltrability ( $80\text{--}8500\text{mmh}^{-1}$ , depending on soil texture). However, the infiltrability of the soil is highly variable due to the ordered structure of vegetation in oil palm plantations. A study in West Sumatra on 10-year-old oil palms demonstrated significant spatial variability when comparing water infiltration rates in soil beneath the palm circle, harvest path, and frond piles. Infiltration rate increased in the order path < circle < frond pile (Fairhurst, 1996). In Papua New Guinea, Banabas *et al.* (2008) recorded similar results (Table 5). They attributed the highest values in the frond pile zones to the macroporosity-enhancing effect of the organic matter present in this zone. They ascribed the lower values found in the weeded circle and harvest-path zones to topsoil compaction from falling bunches in the weeded circle, wheel and foot traffic in the harvest paths, and sparse understory vegetation.

Thus, apart from its high dependence on soil texture, infiltrability will vary temporally and spatially in oil palm plantation. After a strong decrease due to soil compaction after land clearing, infiltrability in oil palm plantation may partly recover due to plant growth and organic matter addition to the soil. Yet, infiltrability will remain low along roads and harvest pathways and in weeded circles.

#### 4.4.2. Leaching and groundwater quality

Leaching losses are generally assumed to be higher in the humid tropics than temperate areas due to the frequent and intense rain storms, higher temperature, and high carbonic acid content in soil (Ah Tung *et al.*, 2009; Johnson

**Table 5** Soil infiltrability ( $\text{mm hr}^{-1}$ ) for major soil types and at specific locations in oil palm plantations

Soil	Frond piles	Between zones	Weeded circles	Harvest path	Source
Typic Hapluland, sandy clay to clay loam	1351	997	270	265	Banabas <i>et al.</i> (2008)
Typic Udivitrand, sandy loam to sand	7350	1230	340	60	Banabas <i>et al.</i> (2008)
Typic Hapludult	2050	—	—	175	Maena <i>et al.</i> (1979)

*et al.*, 1975). Depending on the amount of water draining out of the rooting zone, leached solutes may simply accumulate in a deeper layer of the soil profile or may reach the underlying groundwater (Ah Tung *et al.*, 2009). Table 6 summarizes results from Bruijnzeel (1991), including estimates of annual runoff and nutrient losses in drainage water from tropical rainforests. The author also reported that forest clear-cutting often increased nutrient losses to streams. Brouwer and Riezebos (1998) compared nutrient leaching in closed and logged tropical rainforest in Guyana. Logging clearly increased leaching, which they ascribed to an increased percolation of water through the soil (2800 mm after 22 months logging compared to 1800 mm in closed forest) and increased solute concentrations in the percolating water. They found that Ca, K, and Mg concentrations were 2–10 times greater in the gaps after logging than in closed forest, while the NO<sub>3</sub> concentration was 10–20 times greater than closed forest. The major pulse of leaching occurred during the first year after logging, and most solute concentrations in percolating soil water remained higher up to 15 months after logging. However, vegetative regrowth reduced leaching losses as plants absorbed soluble nutrients and immobilized them in standing stock biomass.

Large nutrient losses are expected in oil palm plantations (Goh *et al.*, 2003). According to Ng *et al.* (2003), most of the oil palm root biomass is found within 1 m of the soil, but the distribution of oil palm active roots favors the nutrient uptake in the upper 30 cm, which may increase the potential risk of nutrient leaching. Omoti *et al.* (1983) measured amounts of nutrients leached under immature (4 years) and mature (22 years) oil palms, distinguishing between the loss of native nutrients and the loss of applied nutrients (fertilizers). The losses of native nutrients from closed and logged tropical forest on one hand and in immature and mature oil palm plantations on the other hand are summarized in Table 7. To our knowledge, there is no chronological study comparing the amounts of nutrient leached under natural forest and oil palm plantation established on the same site neither after forest clearing nor between forested and oil palm catchments with similar climatic and soil conditions. This makes it difficult to quantify the impact of oil palm plantation establishment on native nutrient leaching. The most complete study to assess the impact on hydrological processes of forest conversion to tree crop and oil palm plantations (DID, 1989) did not evaluate leaching, leaving a considerable gap in our knowledge of this process in plantations at the catchment scale.

Despite the paucity of large-scale data on leaching processes, many plot-scale studies investigated the percentage of applied fertilizers lost through leaching in oil palm plantations, some of them comparing young and mature oil palm stands (Chang and Zakaria, 1986; Foong *et al.*, 1983; Maena *et al.*, 1979). For example, a field lysimeter study conducted on Munchong series soil in Malaysia found higher fertilizer losses when the palm was 1–4 years old (17% for N and 10% for K), which declined to 2.1% of applied fertilizer N

**Table 6** Catchment studies of annual rainfall, annual runoff, and nutrient losses in drainage water from South East Asian tropical forests (modified from [Bruijnzeel, 1991](#))

Location	Type of forest	Soil	Catchment area (ha)	Annual rainfall P (mm)	Annual runoff Q (mm)	Q/P (%)	Nutrient losses (kg ha <sup>-1</sup> year <sup>-1</sup> )					Sources quoted by <a href="#">Bruijnzeel (1991)</a>
							Ca	Mg	K	P	N	
Ulu Gombak, Malaysia	Partly disturbed <i>dipterocarp</i> forest	Oxisol	31	2500	750	30	2.1	1.5	11.2	–	–	<a href="#">Kenworthy (1971)</a>
Bt. Berembun, Malaysia	Undisturbed <i>dipterocarp</i> forest	Deep Ultisols (2/3) and Oxisols (1/3), sandy clay (loam)	29.6	2005	225	11	5.8	3.6	8	–	–	<a href="#">Abdul Rahim and Zulkifli (1986)</a> , <a href="#">Zulkifli (1989)</a> , and <a href="#">Zulkifli et al. (1989)</a>
Watubelah, Indonesia	Plantation forest of <i>Agathis dammara</i>	Andesitic tuffs underlain by andesitic breccias	18.7	4670	3590	77	29	30.5	22	0.7	10.6	<a href="#">Bruijnzeel (1983a,c, 1984)</a>
Kinta Valley, Malaysia	Lowland rainforest	Limestone (karst terrain)	–	2845	1605	56	795	90	76	–	–	<a href="#">Crowther (1987a,b)</a>
Ei Creek, Papua	Colline rainforest	Basaltic volcanic agglomerates	16.25	2700	1480	55	24.8	51	14.9	–	–	<a href="#">Turvey (1974)</a>
Gua Anak Takun, Malaysia	Lowland rainforest	Limestone	–	2440	1255	51	764	45	20	–	–	<a href="#">Crowther (1987a,b)</a>

**Table 7** Nutrient leaching losses in undisturbed forest, highly disturbed forest, and oil palm plantations

	Amount of element leached (kg ha <sup>-1</sup> year <sup>-1</sup> )									Source
	Ca	K	Mg	Na	Cl	NH <sub>4</sub> -N	NO <sub>3</sub> -N	N-total	SO <sub>4</sub> -S	
Closed tropical rain forest, Guyana <sup>a</sup>	2	5	1	24	25	1	3	4		Brouwer and Riezebos (2002)
Large gap sikkder zone, Guyana <sup>a</sup>	14	23	16	65	56	1	90	91		Brouwer and Riezebos (2002)
Unfertilized young oil palm (4years), Nigeria	165	3	32	—	53	—	—	32	53	Omoti <i>et al.</i> (1983)
Unfertilized adult oil palm (22years), Nigeria	123	29	32	—	30	—	—	65	83	Omoti <i>et al.</i> (1983)

<sup>a</sup> Annual average on 1030 days.

and 2.7% of fertilizer K when the palm was 5–14 years old (Foong, 1993). Higher nutrient losses through leaching from immature palm implies less plant nutrient uptake, whereas older palms have more extensive root system that can absorb applied and indigenous soil nutrients, a greater nutrient demand and a higher transpiration rate that lowers water loss via leaching. However, a field-scale study on Orlu and Algba series (Rhodic Paleudult) soils in Nigeria showed no significant differences in nutrient leaching from applied fertilizers between the immature (4 years) and mature plantations (22 years) (Omoti *et al.*, 1983). According to some authors, the adult stage poses a high risk of nutrient losses because ground vegetation is sparse due to poor light penetration through the closed oil palm canopy (Breure, 2003). Moreover, the LCC dies off at canopy closure, releasing a large amount of N from the decomposing legume biomass and increasing the risk of N loss via leaching (Campiglia *et al.*, 2010; Goh *et al.*, 2003). According to Goh and Chew (1995), leaching losses also depends on soil texture and greater losses were recorded in sandier soils, as summarized in Table 8. In general, leached P losses are low due to the relative immobility of P in acidic, weathered tropical soils (Goh *et al.*, 2003; Omoti *et al.*, 1983).

A plot-scale study by Ah Tung *et al.* (2009) is the only one to our knowledge that investigated leaching losses of inorganic N and K and measured their concentrations in groundwater. They found leaching losses of inorganic N represented between 1.0% and 1.6% of applied N fertilizer and the K losses were between 2.4% and 5.3%, depending on fertilizer application rates. The concentration of N and K in the soil solution decreased with soil depth, which they explained by nutrient removal and uptake by palm roots, resulting in lower nutrient concentrations in the soil solution with depth. However, another explanation they did not mention is that fertilizers are applied near the soil surface, so the topsoil layers have a higher concentration of nutrients in soil solution; this naturally declines with depth because there was no fertilizer injection deeper in the soil profile. The measured concentrations of  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and K in groundwater ranged from 0.23 to 2.7, 0.07 to 0.25, and 0.63 to  $9.54\text{mg l}^{-1}$ , respectively, which did not exceed the water quality standards set by the World Health Organization (WHO, 2008). The authors did not specify the distance of groundwater sampling wells from the palm circles where the fertilizers were applied. However, they mentioned the possibility of groundwater pollution when excessive N fertilizer was applied or if  $\text{NO}_3\text{-N}$  leached from the soil profile into groundwater in the intertree spaces between palms. This supposition is supported by Schroth *et al.* (2000), who reported pronounced spatial pattern of  $\text{NO}_3\text{-N}$  concentrations within the plantation. Low  $\text{NO}_3\text{-N}$  concentrations were measured in the soil profile within 1 m of palm trees, indicating efficient absorption of mineral N by the palms, whereas soil  $\text{NO}_3\text{-N}$  concentrations increased with increasing distance from palm trees. At 4 m away from the trees, the vertical  $\text{NO}_3\text{-N}$  concentration gave



**Table 8** Nutrients leached as percentages of applied fertilizers in immature (1–4 years) and mature (>4 years) oil palm plantations

Location	Soil	Annual rainfall (mm)	Palms per ha	Age of palm (year)	Nutrient losses of applied fertilizer (%)							Notes	Source
					N	P	K	Mg	Ca	S	Cl		
Nigeria	Rhodic Paleudult	1923	150	4 and 22	34	–	18	172	60	14	141		<i>Omoti et al. (1983)</i>
Sabah, Malaysia	Typic Hapludults	>2500		26	1–1.6	–	2.4–5.3	–	–	–	–		<i>Ah Tung et al. (2009)</i>
Malaysia	Typic Hapludox (Munchong series)	1909	145	1	26.5	Trace	19.5	169.4	–	–	–	Rainfed	<i>Foong et al. (1983)</i>
		1495		2	10.9	Trace	3.4	8.4	–	–	–	Rainfed	
		2729		3	12.2	1.4	10.4	53.6	–	–	–	Irrigated	
		2787		4	16.8	5.8	5.6	47.6	–	–	–	Irrigated	
		2391		5	2.7	1.7	1.9	5.4	–	–	–	Irrigated	
		2193		6	4.8	1.4	3.3	6.6	–	–	–	Irrigated	
Malaysia	Typic Paleudult (Serdang series)	2352	–	–	10.4	–	5.1	–	–	–	–	<i>Chang and Zakaria (1986)</i>	
Malaysia	Typic Hapludox (Munchong series)	–	–	1–4	16.6	1.8	9.7	69.8	–	–	–		<i>Foong (1993)</i>
				5–8	1.2	1.6	2.5	11.5	–	–	–		
				9–14	3.0	1.5	2.9	15.5	–	–	–		

clear evidence of  $\text{NO}_3\text{-N}$  leaching into the deeper subsoil as concentrations almost doubled from surface soil to 175 cm depth ( $6\text{--}11.5\ \mu\text{g g}^{-1}$ , respectively). They concluded that much of the soil volume in the plantation was apparently not accessed by palm roots, leaving surplus N at risk of leaching loss (Schroth *et al.*, 2000).

Thus, nutrient leaching in oil palm plantations may be impacted by soil type and rainfall intensities (that both influence infiltration rates), oil palm age, agricultural practices such as LCC establishment, water management that impacts the water table level and subsequently increases the possibility of leaching, fertilizer types, and rate applications, etc. In oil palm plantations receiving chemical fertilizer, low-nutrient losses via leaching and nutrient concentrations in groundwater quality were generally reported. Higher nutrient losses (as % of fertilizer application) are expected in immature plantations due to lower nutrient uptake by palm roots. However, higher fertilizer applications are recommended in mature plantations, which may lead to higher losses in absolute terms. The link between nutrient leaching and groundwater quality is clearly not fully investigated or understood. A shortcoming of the current literature is the reliance on plot-scale studies with lysimeters installed close to the trees, despite high spatial heterogeneity in the structure of the oil palm plantation that affects soil infiltration rates, distribution of vegetation, and root growth in the soil profile. Although organic fertilizer applications (POME and EFB) also supply nutrients that could potentially leach, impacting groundwater quality, work on oil palm plantations amended with these residuals has focused on soil properties rather than groundwater quality (Okwute and Isu, 2007).

#### 4.5. Surface runoff and erosion

In rainforest watersheds, surface runoff may occur as infiltration excess overland flow and/or saturated overland flow. Malmer (1996) reported that infiltration excess overland flow was more likely than saturated overland flow across the sloping uplands of a tropical forested catchment, whereas areas close to the stream are susceptible to saturated overland flow or return flow. However, infiltration excess overland flow in forests is regarded as a rare phenomenon, as vegetation plays an important role in holding and absorbing rainfall (Bonnell, 2005; Bruijnzeel, 1990; Zhang *et al.*, 2007). Noguchi *et al.* (1997a) concluded that neither saturation overland flow nor infiltration excess overland flow is likely to occur at Bukit Tarek Experimental Watershed, a forested watershed in Peninsular Malaysia. Data on annual runoff soil and nutrient losses in tropical rainforests, reviewed by Bruijnzeel (1990), are summarized in Table 9. Although surface runoff is rare in forests, it is likely in oil palm plantations during short-term high-intensity rainfall events because of the high intrinsic variability in soil infiltrability (Banabas *et al.*, 2008). When runoff does occur, it would be initiated mainly from the

**Table 9** Runoff, soil erosion, dissolved solutes, and sediment losses via runoff in Southeast Asian rainforest

Soil	Study scale	Annual rainfall (P) mm	Runoff (Q) mm	Q/P (%)	Soil erosion	Dissolved loss ( $\text{tha}^{-1}\text{year}^{-1}$ )	TSS outflow ( $\text{tha}^{-1}\text{year}^{-1}$ )	Notes
Red-yellow podsol	Plot $2 \times 10\text{m}$	2862–3563	2.50	0.5	$0.41\text{gm}^{-2}$	–	–	Period 27/3 to 6/6/98; rainfall 495mm
			2.50	0.8	$1.35\text{gm}^{-2}$	–	–	Period 28/12/97 to 21/2/98; rainfall 316mm
Gleyic podsol	Runoff plot $50\text{--}200\text{m}^2$ ; catchment scale	1950	56.55	2.9	$38\text{kg}\text{ha}^{-1}\text{year}^{-1}$	0.16	0.3	Excluding valley bottom

weeded circle (where stem flow causes the highest local water inflows and the infiltrability is quite low) and the harvest-path zone (where infiltrability is lowest due to soil compaction) (Table 10).

While erosion is never excessive (i.e., greater than the rate of soil formation) in forests, soil loss can be pronounced at particular stages in an oil palm plantation. Many studies reported highest erosion rates immediately after land clearing, resulting from increased exposure of the soil surface to erosion and surface runoff losses (Bruijnzeel, 1990, 2004; Douglas, 1999; Goh *et al.*, 2003). According to Clay (2004), bare soil resulting from road construction and other infrastructure such as bridges, culverts, and drains increases soil erosion in oil palm plantations. DID (1989) showed that deforestation activities such as timber harvesting, construction of roads, and preparation of land for crop planting account for as much as 91% of all the sediment exported from the catchments. Results from erosion plots on two soil types revealed five to seven times more erosion from deforested land than forested lands during the first year after planting the LCC. However, once the ground cover was established, erosion was greatly reduced but not eliminated (DID, 1989). In mature plantations, erosion still occurs from harvest paths, roads, and localized areas of steep elevation. Clay (2004) reported that in Papua New Guinea, every 100m of road has the potential to produce as much sediment as each hectare of oil palm, but this is not unrelated as there are 50 linear meters of road for every hectare of oil palm planted.

Some authors estimated contribution of rainfall to runoff and associated nutrient losses, usually expressed as percentage of applied fertilizers, carrying out plot-scale studies in oil palm plantations. Some of them computed nutrient losses, via runoff and/or sediment transport to be large, accounting for up to 10% of applied fertilizers (Maena *et al.*, 1979). They observed greater losses from surface runoff in the uncovered soil in the harvest path, compared to the interrows, where pruned fronds provide soil cover (Fairhurst, 1996; Goh *et al.*, 2003; Maena *et al.*, 1979). Others reported low losses of nutrient via runoff in oil palm plantation (Banabas *et al.*, 2008). Results from key papers are summarized in Table 11. Moreover, runoff losses of applied fertilizers also depend on the lag time between the application and the subsequent rainfall. While Chew *et al.* (1995) showed that high rainfall prior to fertilizer application resulted in substantial nutrient loss, Kee and Chew (1996) found that the first rain event following fertilizer application in a wet month gave N concentrations in runoff water of 89 and 135 mgkg<sup>-1</sup> for 65 and 130kgN ha<sup>-1</sup> rates, respectively, compared to 4mgN kg<sup>-1</sup> in the unfertilized control plot. Thus, the amount of fertilizer nutrients lost through runoff and sediment transport depends on the soil texture, the age of the oil palms, the local topography and infiltrability, and the lag time between fertilizer application and rainfall (Banabas *et al.*, 2008). The continual compaction of harvest pathways and roads and the disappearance of

**Table 10** Soil erosion and nutrient losses in surface runoff water from spatial components of an oil palm plantation on a Typic Hapludult in Malaysia (after [Goh \*et al.\*, 1999](#); [Maena \*et al.\*, 1979](#))

Fertilizer placement	Average annual runoff (% of rainfall)	Soil erosion ( $\text{tha}^{-1}\text{year}^{-1}$ )	Nutrient losses (% of applied fertilizer)					
			N	P	K	Mg	Ca	B
Oil palm row	20.2	7.47	13.3	3.5	6.0	7.5	6.8	22.9
Harvest path	30.6	14.92	15.6	3.4	7.3	4.5	6.2	33.8
Fronde pile	2.8	1.1	2.0	0.6	0.8	2.7	0.8	3.3
Fronde pile/harvest path	—	—	6.6	1.4	3.5	2.2	3.4	12.5
Average for the field	—	—	11.1	2.8	5.0	5.6	5.2	20.7
Fertilizer nutrients applied ( $\text{kgha}^{-1}$ )			90.2	52.0	205.9	32.8	78.9	2.4

**Table 11** Nutrient losses through runoff and eroded sediment in oil palm plantations (plot-scale studies)

Location	Soil	Age of oil palm plantation	Annual rainfall (mm)	Annual runoff (% of rainfall)	Annual nutrient losses, $\text{kg ha}^{-1} \text{ year}^{-1}$ (% of applied fertilizers)					Transport	Source
					N	P	K	Mg	Ca		
Malaysia	Orthoxic Tropudult	11	1426	2.8–30.6%	9.93 (11.1%)	1.43 (2.8%)	10.40 (5.0%)	1.82 (5.6%)	4.04 (5.2%)	In runoff	<a href="#">Maena et al. (1979)</a>
					5.57 (6.2%)	3.63 (7.0%)	8.79 (0.0%)	21.10 (64.3%)	7.40 (9.4%)	In eroded sediment	
Malaysia	Typic Paleudult				4.5–7.2 (4.4–7.2%)	0.7–1.1 (0.5–0.8%)	20.8–33.0 (9.7–15.4%)	3.6–6.8 (4.0–7.6%)	–	In runoff	<a href="#">Kee and Chew (1996)</a>
					0.5–0.8 (0.5–0.9%)	0.5–1.3 (0.3–0.9%)	Trace	0.1 (0.1%)	–	In eroded sediment	
PNG	Typic Hapluland	Mature (135 palms $\text{ha}^{-1}$ )	2398 ± 374	6 (0–44 for individual events)	2.2	–	–	–	–	In runoff	<a href="#">Banabas et al. (2008)</a>
PNG	Typic Udivitrand	Mature (135 palms $\text{ha}^{-1}$ )	3657 ± 682	1.4 (0–8 for individual events)	0.3	–	–	–	–	In runoff	

PNG, Papua New Guinea.

understory cover (including LCC) due to canopy closure may also contribute to soil and nutrient losses via runoff and erosion within a mature oil palm plantation (Table 11).

## 4.6. Stream flow and stream water quality

### 4.6.1. Stream flow

Hydrological changes observed at the plot scale will have consequences on stream flow and water quality. It is well known that total stream flow increases following clearance of forest cover and conversion to other types of land use (Bruijnzeel, 1990). The absence of vegetation allows a greater proportion of direct rainfall to reach the forest floor, and reduced ET rates (due to absence of plants) translate into a greater volume of water leaving the catchment. When land-use change increases the amount of disturbed and compacted surfaces, there will be an associated increase in surface runoff and stream flow. This increase may be permanent when converting natural forest to grassland or shallow-rooted agricultural crops, or temporary in the case of conversion to tree plantations (Abdul Rahim and Harding, 1992; Bruijnzeel, 1990).

Hydrological studies carried out in oil palm plantation at a watershed scale are scarce, except those of Sungai Tekam Experimental Basin in Pahang by DID (1989). They observed an increase in total flow immediately in response to deforestation (+85 to 157% for the first 3 years after deforestation), which declined gradually with the planting of LCC and tree crops. Total flow increase was due to greater baseflow rather than more runoff. The authors ascribed the large increase in baseflow to rising water table level due to reduced ET and ponding effects immediately after deforestation, as felled logs and debris were left in the stream channels for long period acting as debris dams. However, in Bruijnzeel's review (2004), other authors reported a decrease in baseflow following deforestation, especially during the dry season because more surface runoff from compacted soils decreased the groundwater recharge and the subsequent release of baseflow. Soil compaction following land clearing triggers a shift from dominant subsurface flow to overland flow, increasing peak flow during storm events (Bruijnzeel, 2004). DID (1989) observed also that peak discharge increased after deforestation and that time-to-peak decreased significantly from 3 to 1 h immediately after deforestation. Although this study provides insight into short-term hydrological changes when oil palm plantations are established, it was stopped before the oil palm plantation reached maturity (Hui, 2008). Further study of the mature plantation would be helpful to determine whether older oil palm plantations continue to experience more surface runoff and higher peak flows during storms than undisturbed forest, leading to higher stream flow in the watershed. A study in a small oil palm catchment (8.2ha) on a coarse sandy clay loam Ultisol in the upstream of

Skudai River in Johor, Malaysia, showed a high proportion of baseflow, approximately 54% of the total runoff and rapid responses to rainfall with a short time (6–48 min) to peak flow (Yusop *et al.*, 2007). However, baseflow can be higher in forested catchments and reach as much as 70% of the total annual flow (Abdul Rahim and Harding, 1992; Yusop *et al.*, 2007).

#### 4.6.2. Stream water quality

It is clear that oil palm plantations have different hydrological characteristics from natural forests at the plot scale, which may impact the quality of receiving waters at a watershed scale. The increase of surface runoff loaded with eroded soil particles, the use of agrochemical (fertilizers and pesticides), and the release of POME in the streams are expected to affect the aquatic life and drinkable water quality of the receiving water bodies (ECD, 2000; Sheil *et al.*, 2009). However, catchment-scale studies on water quality and nutrient losses in tropical areas have focused primarily on forested areas and the impacts of rainforest disturbances (Malmer, 1996; Malmer and Grip, 1994). In Malaysia, some researchers reported slightly acidic stream water, low electrical conductivity, and low solute concentrations from forested catchments (DID, 1989; Yusop *et al.*, 2006) and in a catchment with diversified land uses, including oil palm plantation (15%), forest (50%), mining, and urbanized area (Gasim *et al.*, 2006) (Table 12). As expected, deforestation greatly increased outflow of sediment loads and nutrients after clearing (e.g., EC (+16%), Ca (+26%), and Mg (+37%) by DID, 1989; turbidity ( $\times 9$ ) and suspended solids ( $\times 12$ ), Zulkifli *et al.*, 1987). Temporal variations of stream water quality at the storm event scale were noted by Yusop *et al.* (2006), in particular higher export of nitrates ( $\times 3$ ) and suspended solids in stormflow than in baseflow but greater export of  $\text{SiO}_2$  during baseflow, suggesting that low flow removed solutes associated with soil weathering processes. At the seasonal scale, Gasim *et al.* (2006) observed higher values for most water quality parameters in the wet season than the dry season, while DID (1989) observed higher values for turbidity, suspended solids, and iron in wet season and higher values of conductivity, pH, Mg, and Ca during dry months.

In large oil palm plantations, POME is released directly to streams, sometimes without treatment, which is expected to cause water pollution (cf. Section 2.2.4). To our knowledge, the study by Olaleye and Adedeji (2005) is the only one published in the peer-reviewed literature to assess the water quality of a river impacted by POME release from oil palm plantations. They ascribed the near absence of zooplankton in a large Nigerian river to the deleterious effect of POME discharge in the stream. Pesticides originating from oil palm plantations are expected to have a strong impact on water quality according to NGOs, while oil palm managers expect low impact due to low application rates. The absence of data on this topic in the peer-reviewed literature is a major knowledge gap.



**Table 12** Water quality in streams as impacted by oil palm plantation, managed and natural forest catchments in Southeast Asia (Malaysia)

Land use	Soil	Annual rainfall (mm)	Notes	pH	EC ( $\mu\text{s cm}^{-1}$ )	Turbidity (NTU)	DO ( $\text{mg l}^{-1}$ )	TDS ( $\text{mg l}^{-1}$ )	TSS ( $\text{mg l}^{-1}$ )	K ( $\text{mg l}^{-1}$ )	Ca ( $\text{mg l}^{-1}$ )	Mg ( $\text{mg l}^{-1}$ )	Na ( $\text{mg l}^{-1}$ )	NH <sub>3</sub> ( $\text{mg l}^{-1}$ )	NO <sub>3</sub> ( $\text{mg l}^{-1}$ )	PO <sub>4</sub> ( $\text{mg l}^{-1}$ )	Cl ( $\text{mg l}^{-1}$ )	SO <sub>4</sub> ( $\text{mg l}^{-1}$ )	SiO <sub>2</sub> ( $\text{mg l}^{-1}$ )	Source
Variably vegetated with 50% forest and 15% oil palm	—	2235		3.2–6.3	14.3–85.7	4.7–28.7	0.3–6.4	22.7–184	1.2–79.1					0.007–0.57	0.7–2.9	0.0–0.50		0.0–2.0		Gasim <i>et al.</i> (2006)
Two-forested catchments (~30 ha)	Araceneous series (derived from sandstone)	2348–3169	Low flow Storm flow	5.6 5.1–5.2	7.3–7.5 10.2–11.6					0.34–0.38 0.83–0.92	0.17–0.19 0.2–0.24	0.32–0.35 0.37–0.45	0.25–0.28 0.2–0.21	0.03 0.04	0.08–0.1 0.23–0.32	0.1	0.4–0.5 0.6	0.005 0.005	9.23–9.24 5.15–6.34	Yusop <i>et al.</i> (2006)
Forested control catchment (56 ha)	Tropeptic Harplothox	1878	6 years average	6.9	55.7	48.6			30.1	1.48	6.81	2.48	3.36		1.29				26.50	DID (1989)
Cleared catchment for oil palm (97 ha)	Tropeptic Harplothox	1878	6 years average	7.0	83.6	43.2			47.8	2.56	9.04	3.83	2.94		1.55				20.49	DID (1989)

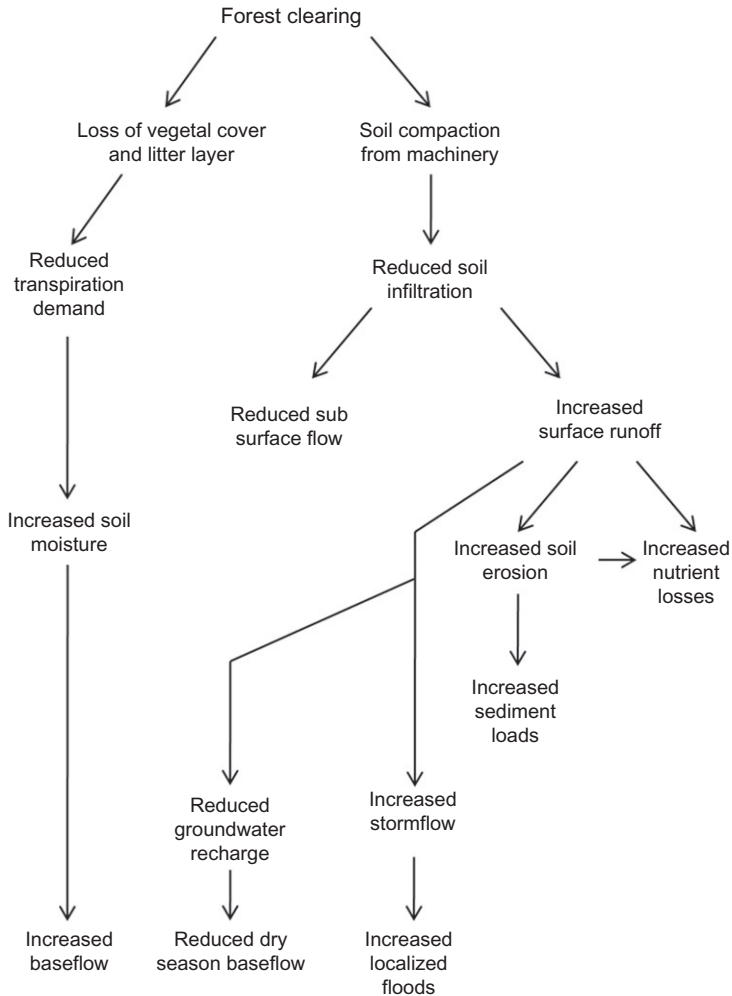
Despite the potential risk of water pollution expected from oil palm plantation activities, there have been very few studies at the watershed scale to assess water quality in streams within a plantation at different development stages (i.e., immature vs. mature palms).

#### 4.7. Synthesis

There is an abundance of literature on hydrological processes in tropical rainforest ecosystems, immediate and short-term impacts of rainforest disturbance (logging, clearing), as depicted in Fig. 5. It is generally accepted that natural regrowth in tropical forests leads to a relatively fast return to previous levels of soil infiltrability, streamflow, water budget, and soil nutrient stocks. However, the impact of oil palm establishment on changes to hydrological processes and associated nutrient losses and their evolution during oil palm growth are much less investigated, documented, and understood.

Table 13 summarizes the evolution of hydrological processes and associated nutrient losses occurring from forested land to mature oil palm plantation stage, based on observed or expected outcomes and highlights research gaps in the understanding of these processes. We compare consecutive stages (cleared land vs. tropical forest; immature plantation vs. cleared land; mature vs. immature plantation) and also compare both immature and mature stages to forest, the original land cover. Expected trends for each stage are described qualitatively because observations were often made for a specific plantation age (without long-term monitoring to cover all stages) across areas with a broad range of climatic and soil conditions. The impacts of forest clearing rely on many studies reviewed by Bruijnzeel (1990, 1991) that generally reported strong impacts of complete forest clearing. Information regarding the immature oil palm stage is based on the study by DID (1989), that represents, to our knowledge, the only chronological study focused on the evolution of hydrological process dynamics from forest to oil palm plantation establishment, at both plot scale and watershed scale. Unfortunately, it was stopped before oil palms reached maturity and did not investigate leaching process at the plot scale. It concluded that after clearing, the growth of oil palm (with LCC) tends to counteract the negative impacts of clearance, without always returning to predisturbance levels. Runoff and erosion remain high in compacted areas such as roads, harvest paths, and weeded circles. Due to the high nutrient-uptake rate and large evaporative demand of the palms, low-nutrient losses via leaching were generally reported in oil palm plantations in Southeast Asia despite high-rainfall intensities.

Few studies compared the water and nutrient budgets between young and mature oil palm stands, although leaching losses at the plot scale were examined by Foong *et al.* (1983) and Omoti *et al.* (1983) and ET was measured by Yusop *et al.* (2008). In mature plantations, data were available from a number of plot scale focusing on single hydrological processes, such



**Figure 5** Hydrological impacts of forest clearing (modified from [Henson, 1999](#)).

as runoff or leaching, with the exception of [Banabas \*et al.\* \(2008\)](#). Investigating water budget in a mature plantation, including ET, soil water storage, runoff, and leaching losses, authors demonstrated that nutrient losses occurred primarily from leaching rather than from runoff. Few studies have taken in account the spatial heterogeneity of the plantation. Finally, hydrological studies carried out at the watershed scale in mature oil palm plantation are almost nonexistent, with the exception of [Yusop \*et al.\* \(2008\)](#) who quantified runoff processes on a small oil palm watershed (8.2ha). The only research on stream water quality within oil palm plantations

**Table 13** Qualitative description of the expected change in hydrological processes and associated nutrient losses from forest clearing to mature oil palm plantation, compared to undisturbed tropical forest

Hydrological process	Clearance (bare soil)	Immature oil palm plantation		Mature oil palm plantation	
	Versus forest	Versus clearance	Versus forest	Versus immature	Versus forest
<i>Plot scale</i>					
Infiltration rate	↘ <sup>a,b</sup>	↘ <sup>b</sup>	↑ <sup>b</sup>	—	↕ <sup>c,d</sup>
Leaching	↗ <sup>a</sup>	↘ <sup>e<sup>a</sup></sup>	↑ <sup>e<sup>c</sup></sup>	↘ <sup>e</sup> or = <sup>f</sup>	↑ <sup>g,h</sup>
Actual evapotranspiration	↘ <sup>a</sup>	↘ <sup>e<sup>b</sup></sup>	↓ <sup>e<sup>a,i</sup></sup>	—	= <sup>a,c</sup>
Runoff and erosion	↗ <sup>a,b</sup>	↘ <sup>b</sup>	↑ <sup>b</sup>	—	↑ <sup>e<sup>g</sup></sup>
<i>Catchment scale</i>					
Water yields	↗ <sup>b</sup>	↘ <sup>b</sup>	↑ <sup>b</sup>	—	—
Dry season flow	↘ <sup>a</sup>	—	—	—	—
Stormflow	↗ <sup>a</sup>	↘ <sup>a,b</sup>	↑ <sup>e<sup>a</sup></sup>	—	↑ <sup>e<sup>g</sup></sup>
Peakflow	↗ <sup>b</sup>	↘ <sup>b</sup>	↑ <sup>b</sup>	—	↑ <sup>e<sup>g</sup></sup>
Time to peak	↘ <sup>b</sup>	↗ <sup>b</sup>	—	—	—
Nutrient outflow	↗ <sup>a,b</sup>	↘ <sup>b</sup>	↑ <sup>b</sup>	—	↑ <sup>e<sup>g</sup></sup>
Sediment loads in stream	↗ <sup>b</sup>	↘ <sup>b</sup>	↑ <sup>b</sup>	↘ <sup>e<sup>a,b</sup></sup>	↑ <sup>e<sup>g</sup></sup>

↘, decrease; ↗, increase; ↑, higher; ↓, lower; ↕, variable; e, expected; =, similar.

<sup>a</sup> Bruijnzeel (1990).

<sup>b</sup> DID (1989).

<sup>c</sup> Banabas *et al.* (2008).

<sup>d</sup> Maena *et al.* (1979).

<sup>e</sup> Foong (1993).

<sup>f</sup> Omoti *et al.* (1983).

<sup>g</sup> ECD (2000).

<sup>h</sup> Schroth *et al.* (2000).

<sup>i</sup> Ling (1979) (quoted by Bruijnzeel, 1990).

agroecosystems comes from DID (1989) for immature plantations. Thus, hydrological process dynamics and magnitude (e.g., total water yields, dry season baseflow, stormflow dynamics) and nutrient outflows from oil palm plantation are far from being fully assessed and understood.

## 5. CONCLUSION

Since the 1960s, research effort focused on plot-scale trials in South-east Asia to provide agronomic recommendations for plantation managers that would increase productivity and economic returns for the palm oil industry. Growing awareness of environmental impacts from the rapidly

expanding oil palm sector, driven by media and socioenvironmental NGOs, led to the creation of RSPO to promote a sustainable palm oil production. This organization encourages planters to assess the environmental impacts of oil palm cultivation and develop eco-friendly agricultural practices. Although RSPO encourages an evaluation of oil palm plantation activities impacting water quality and hydrological processes, this review demonstrated that the topic remains largely underinvestigated. First of all, the actual agricultural practices for nutrient and water management currently used in Southeast Asian oil palm plantations are poorly described, especially in smallholdings. Assessing actual agricultural practices is challenging as high variability likely occurs not only between large companies and smallholders but also within both production systems, due to variable access to knowledge, technical, and financial means. Another constraint is that palm oil is produced in developing countries, which may lack the resources to monitor the impact of oil palm plantation on hydrological functions at different stages throughout its long lifespan (about 25 years). Indeed, most of hydrological studies in oil palm plantations were carried out at the plot scale (i.e., a few hectares), whereas oil palm plantations can reach thousands contiguous hectare across several watersheds. Few studies provided an integrated view of hydrological processes or have taken account of the intrinsic spatial variability of an oil palm plantation. Spatiotemporal variation in surface water quality and groundwater quality within oil palm plantations has been very poorly investigated, and the link to agricultural practices remains tenuous. Therefore, study cases that include a survey of actual agricultural practices, water quality assessment, and hydrological processes investigation at the watershed scale are needed to better understand and assess the potential risk to waterways of oil palm plantations. In the end, this information will help planters to manage their oil palm plantations more sustainably.

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