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Ecosystem functions of oil palm plantations
–
a review

Claudia Dislich, Alexander C. Keyel, Jan Salecker, Yael Kisel, Katrin M. Meyer, Marife D. Corre, Heiko Faust, Bastian Hess, Alexander Knohl, Holger Kreft, Ana Meijide, Fuad Nurdiansyah, Fenna Otten, Guy Pe'er, Stefanie Steinebach, Suria Tarigan, Teja Tscharntke, Merja Tölle, and Kerstin Wiegand

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Georg-August-Universität Göttingen
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Abstract: Oil palm plantations have expanded rapidly in the last decades. This large-scale land-use change has had great impacts on both the areas converted to oil palm and their surroundings. However, research on the impacts of oil palm agriculture is scattered and patchy, and no clear overview exists. Here, we address this gap through a systematic and comprehensive literature review of all ecosystem functions in oil palm plantations. We compare ecosystem functions in oil palm plantations to those in forests as forests are often cleared for the establishment of oil palm. We find that oil palm plantations generally have reduced ecosystem functioning compared to forests. Some of these functions are lost globally, such as those to gas and climate regulation and to habitat and nursery functions. The most serious impacts occur when land is cleared to establish new plantations, and immediately afterwards, especially on peat soils. To variable degrees, plantation management can prevent or reduce losses of some ecosystem functions. The only ecosystem function which increased in oil palm plantations is, unsurprisingly, the production of marketable goods. Our review highlights numerous research gaps. In particular, there are significant gaps with respect to information functions (socio-cultural functions). There is a need for empirical data on the importance of spatial and temporal scales, such as the differences between plantations in different environments, of different sizes, and of different ages. Finally, more research is needed on developing management practices that can off-set the losses of ecosystem functions.

Keywords: ecosystem functions, ecosystem services, biodiversity, oil palm, land-use change, Elaeis guineensis, review

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Ecosystem functions of oil palm plantations: a review

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ABSTRACT
Oil palm plantations have expanded rapidly in the last decades. This large-scale land-use change has had great impacts on both the areas converted to oil palm and their surroundings. However, research on the impacts of oil palm agriculture is scattered and patchy, and no clear overview exists. Here, we address this gap through a systematic and comprehensive literature review of all ecosystem functions in oil palm plantations. We compare ecosystem functions in oil palm plantations to those in forests as forests are often cleared for the establishment of oil palm. We find that oil palm plantations generally have reduced ecosystem functioning compared to forests. Some of these functions are lost globally, such as those to gas and climate regulation and to habitat and nursery functions. The most serious impacts occur when land is cleared to establish new plantations, and immediately afterwards, especially on peat soils. To variable degrees, plantation management can prevent or reduce losses of some ecosystem functions. The only ecosystem function which increased in oil palm plantations is, unsurprisingly, the production of marketable goods. Our review highlights numerous research gaps. In particular, there are significant gaps with respect to information functions (socio-cultural functions). There is a need for empirical data on the importance of spatial and temporal scales, such as the differences between plantations in different environments, of different sizes, and of different ages. Finally, more research is needed on developing management practices that can off-set the losses of ecosystem functions. Our findings should stimulate research to address the identified gaps, and provide a foundation for more systematic research and discussion on ways to minimize the negative impacts and maximize the positive impacts of oil palm agriculture.

Key words: ecosystem functions, ecosystem services, biodiversity, oil palm, land-use change, *Elaeis guineensis*, review

I. INTRODUCTION

Over the last decades oil palm plantations have expanded dramatically, especially in Southeast Asia (e.g., Koh 2011, Fig. 1). As the production of palm oil is highly cost- and area-effective compared to other oil crops (e.g., Majer et al. 2009, Zimmer 2010), this trend is projected to continue. In the last years, the scientific community has given increasing attention to oil palm expansion and its consequences for ecosystems and people, but such research has been fragmented by discipline. While natural scientists have mostly focused on the contributions of oil palm expansion to biodiversity loss and global warming, economists have stressed opportunities for development, and social scientists have drawn attention to conflicts between local people and oil palm companies. However, research on the environmental impacts of oil palm agriculture is scattered and patchy, and no clear overview exists. An ecosystem functions approach synthesizes information from natural scientists, economists, and social scientists. Questions about overall impacts cannot be addressed without a comprehensive assessment of the overall picture based on a consideration of all ecosystem functions. Here we present an overview of the consequences of oil palm expansion using ecosystem functions as our unifying framework.

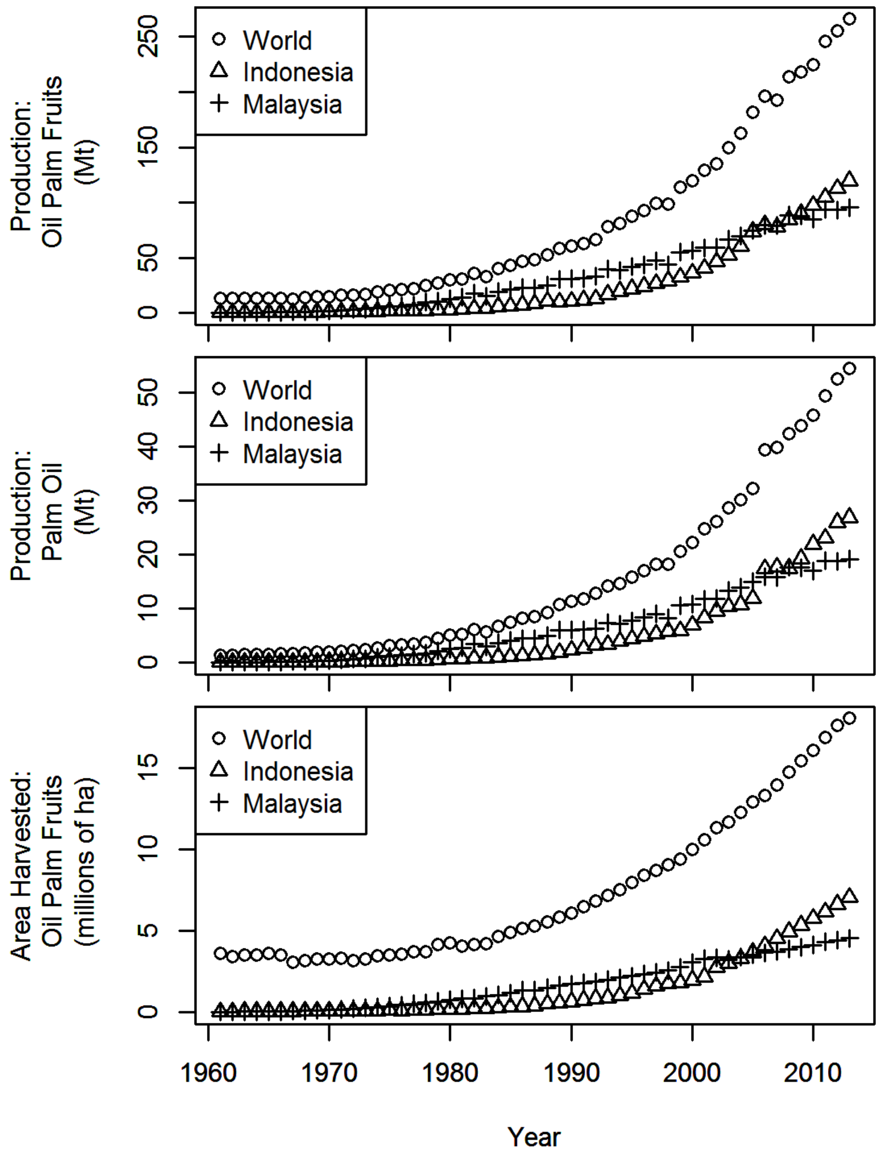

Fig. 1. Production of oil palm fruits, palm oil, and hectares of oil palm harvested have all increased over time globally and for the two main oil palm producers. Hectares planted were calculated based on production and yield estimates. Data source: FAO 2015.

(1) Oil palm agriculture

Elaeis guineensis Jacq., the species most used for palm oil production, originated in Africa, and its native range extends from Guinea to Angola (Corley and Tinker 2003). Oil palms are now grown throughout the humid tropics, in at least 43 countries (Sheil et al. 2009, FAO 2015), though most of the world's plantations are in Malaysia and Indonesia, which now account for about 85% of global crude palm oil production (FAO 2015). As of 2013, approximately 18.1 million hectares are taken up by oil palm plantations, of which about 4.6 million hectares are in Malaysia and 7.1 million hectares are in Indonesia (Fig. 1, FAO 2015).

Easy establishment, low costs, and high output make palm oil a highly profitable tropical cash crop and the most efficient oil crop in the world. Oil palms grow on a range of soil types, including problem soils where few other crops grow successfully (Corley and Tinker 2003). The costs of palm oil production are low because oil palms require little fertilizer and are affected by few pests and diseases, and palm oil mills can be powered by waste biomass from plantations (Basiron 2007, Zimmer 2010).

The establishment of an oil palm plantation begins with clearing the land, either mechanically or with fire. Mechanical clearing requires heavy machinery, which may be expensive and can lead to soil compaction (Lal 1996). Clearing through burning removes some roots and soil as well as above ground biomass, but involves high environmental costs (e.g., Schrier-Uijl et al. 2013, more details below). Despite laws prohibiting the clearing of land with fire, (i.e., since the 1990's in Malaysia and Indonesia), it remains common because it is often cheaper and requires no heavy machinery (Murdiyarso et al. 2004, DeFries et al. 2008). If a plantation is being established on peat soil, the next step is drainage, again with serious environmental costs, as oil palms cannot grow on waterlogged peat soils (Comte et al. 2012). Next, roads are built, along with drainage ditches and, in some cases, terraces. Oil palm seedlings are then planted, 110 to 150 per hectare (Sheil et al. 2009). After 2-3 years, the trees mature and fruits begin to be harvested. Their production peaks at 9-18 years (USDA FAS 2012), but trees are left in the ground until they become too tall to harvest, at 25-30 years old (Basiron 2007, Sheil et al. 2009). At this point, the palms are usually cut down and new seedlings planted. See Figs. 2 and 3 for examples of oil palm plantations in different stages of growth. Crude palm oil (CPO, see Table 1 for a list of abbreviations) and palm kernel oil (PKO) are the main products produced by oil palm plantations, while empty fruit bunches (EFB) and palm oil mill effluent (POME) are the main organic wastes produced.

Oil palm plantations usually occur either in very large estates (3000 to 20000 ha, Sheil et al. 2009) or in very small family-based estates (usually < 50 ha, most around 2 ha, Vermeulen and Goad 2006). Large estates usually include a processing mill, and are mainly owned by private companies, with a minority owned by governments. Smallholder estates make up about 40% of the land under oil palm cultivation in Indonesia and 13% in Malaysia (Indonesia Palm Oil Statistics for 2011, cited by Brandi et al. 2013, Malaysian Palm Oil Board 2012, cited by Azhar et al. 2014).

a)

b)

c)

Fig. 2. Examples of oil palm plantations (Jambi, Indonesia) in different stages of establishment: (a) initial establishment, (b) a young plantation, and (c) a mature oil palm plantation. Photographs by Oliver van Straaten, 2010.

a)

b)

Fig. 3. Two additional examples of oil palm plantations (Jambi, Indonesia). The plantation in (a) is at the establishment stage, this time replacing a former rubber plantation (photograph by Suria Tarigan, 2014) while (b) is the view from a climate tower overlooking the oil palm plantation canopy (photograph by Ana Meijide, 2015).

Smallholders either work independently or as "supported smallholders". Independent smallholders are self-financed, managed, and equipped and may deal directly with the local mill operators of their choice or process their own palm oil using personal or community manual palm oil presses. Supported smallholders are linked to larger producers, for instance through Nucleus Estate Schemes, in which a core estate is surrounded by associated smallholder estates. These schemes are often part of government farmer resettlement programs. "Supported smallholders" receive help in the form of material inputs, training, and/or plantation preparation (Sheil et al. 2009). In return for this assistance, smallholders commit to selling their crops to a company at a set price to be processed at the company's nearby mill, with a proportion of any loans received deducted from the revenue. For example, under the "nucleus estate" model of the 1990s utilized in the villages of Jambi province (Indonesia), the plantation estate developed 30% of the scheme land for its core plantation while 70% was returned to participating smallholders. In the last decade, the "partnership" model has replaced the "nucleus estate" model, and depending upon negotiations in the field, the core estate is only obliged to return 20% of the scheme land to villagers, retaining up to 80% of the land as its core estate. This wide range of owners and management structures of oil palm plantations means that there is also a large range of management practices used, making it more difficult to generalize about oil palm impacts.

Table 1. Abbreviations used in this document

Abbreviation	Definition
CPO	Crude palm oil
EFB	Empty fruit bunches
GHG	Greenhouse gases
K	Potassium
Mg	Magnesium
N	Nitrogen
P	Phosphorus
PKO	Palm kernel oil
POME	Palm oil mill effluent
VOC	Volatile organic compounds

(2) Our approach

Here we address the impacts of oil palm agriculture using the lens of ecosystem functions. Ecosystem functions are defined as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly", and consequently are a subset of ecological processes and ecosystem structures (de Groot et al. 2002). As defined by de Groot et al. (2002), there are 23 ecosystem functions, grouped into four main categories: regulation, habitat, production, and information. Regulation functions maintain biogeochemical cycles, e.g. carbon sequestration, water and nutrient cycling. Habitat functions support biological and genetic diversity. Production functions provide natural resources for human use. Finally, information functions are the cultural, aesthetic, and educational values of ecosystems (de Groot et al. 2002). For the purposes of this review, we have grouped related functions together, so that we discuss 14 ecosystem functions (Table 2).

We reviewed these ecosystem functions systematically to assess the change in ecosystem function relative to forest, to summarize mitigation actions that can be taken to maintain ecosystem functions, to assess which ecosystem functions are understudied, and to highlight important research gaps remaining for each ecosystem function. Where data are available, we discuss differences in ecosystem functioning between large-scale and smallholder-run plantations. We also consider the spatial and temporal scales at which changes in ecosystem functioning occur (Rodríguez et al. 2006).

II. METHODS

We based our review on the list of 23 ecosystem functions from de Groot et al. (2002). We combined strongly related functions, resulting in a working list of 14 ecosystem functions (Table 2). For each of these functions we developed a list of search terms. We then used the search terms in combination with ”oil palm”, ”palm oil”, or ”elaeis guineensis” to search ISI Web of Knowledge for the time frame 1970 to mid-February 2015. We identified relevant studies by scanning titles and abstracts of the articles returned by our searches. These studies, plus additional relevant articles and reports that were found during the preparation of the review, were organized as a JabRef literature database (available from authors upon request). Where available, we used recent reviews as a starting point (e.g., Foster et al. 2011, Comte et al. 2012) Due to the large number of publications for some ecosystem functions, we cannot give an exhaustive overview of all studies. Instead, we report the most relevant findings.

We focus our review on ecosystem functions in monoculture plantations. In their native range, oil palms are often grown in mixed-species agroforestry systems (Poku 2002), which we expect to be quite different in terms of ecosystem functioning from monoculture plantations. However, such farms make up only a tiny fraction of world oil palm production, consequently we focus on ecosystem functions in monoculture plantations.

We focus on ecosystem functions both within and immediately surrounding oil palm plantations - in other words, the direct, local impacts - rather than downstream effects of palm oil use or indirect effects of the oil palm industry. In-depth discussions about these indirect impacts would be too much for one review to cover, and can be found elsewhere (e.g., Sheil et al. 2009, Achten and Verchot 2011).

We use forests as a reference point because they are the natural ecosystem in most areas where oil palm plantations are established. We do not distinguish between primary and secondary forests because data on the differences between them in ecosystem functioning are sparse, and these differences are expected to be small compared to the differences between either type of tropical forest and oil palm plantations. We exclude studies which exclusively compare oil palm to non-forest land-use types. We are aware that oil palm plantations sometimes replace degraded or previously cultivated land rather than forest (Wicke et al. 2008). However, large swathes of forest have been and are still being cleared for oil palm

(Casson 1999, Koh and Wilcove 2008, Wicke et al. 2008, Sheil et al. 2009), and this comparison provides a useful upper bound for possible changes in ecosystem function.

Table 2. Summary of the number of relevant studies found in the literature search.

Ecosystem Function[1]	Studies
Gas & climate regulation	193
Water regulation & supply	87
Disturbance prevention	54
Soil formation & retention	57
Nutrient regulation	99
Waste treatment	36
Pollination	36
Biological control	96
Refugium & nursery functions	218
Food & raw materials	136
Genetic resources	48
Medicinal resources	74
Ornamental resources	2
Information functions	30
Total[2]	902

[1] The following ecosystem functions from de Groot et al. 2002 were combined: *Gas regulation* and *Climate regulation*; *Water regulation* and *Water supply*; *Soil retention* and *Soil formation*; *Refugium function* and *Nursery function*; *Food* and *Raw materials*; and *Aesthetic information*, *Recreation*, *Cultural & artistic information*, *Spiritual & historic information*, and *Science & education*. This resulted in 14 instead of 23 ecosystem functions.

[2] Note that a study may be in more than one category, hence the sum of the number of studies exceeds the total number of studies.

III. RESULTS

In total, we found 902 studies and reports dealing with ecosystem functions in oil palm plantations (Table 2), with a steep increase in publication rate over time (Fig. 4a). Studies were not evenly distributed among ecosystem functions, with some functions (e.g., *Gas & climate regulation* and *Refugium & nursery functions*) receiving a disproportionate share of attention, while others are relatively understudied (e.g., *Pollination & ornamental resources*). Overall, oil palm had a predominantly negative effect on 11 of the 14 ecosystem functions relative to native rainforest (Fig. 5). However, for many ecosystem functions, oil palm had both positive and negative effects.

(1) Regulation functions

(a) Gas & climate regulation

Gas and climate regulation refers to biotic and abiotic processes influencing the atmosphere, including biogeochemical cycles which affect atmosphere composition and are associated with greenhouse gas (GHG) emission and air quality, as well as biophysical processes which regulate climate through energy and momentum fluxes, albedo and water regulating mechanisms. Gas and climate regulation is one of the most studied ecosystem functions in the context of oil palm expansion (Fig. 4b and Table 2). Most available studies focused on emissions of GHG and volatile organic compounds (VOC), a precursor of tropospheric ozone, from oil palm plantations. The replacement of forest by oil palm plantations represents a large loss in gas and climate regulation function. Typically, the carbon sequestered by oil palms does not balance out the GHG emitted as a result of land-clearing fires and GHG emission from fallow land and plantation establishment. Also, VOC emissions from oil palms are higher than for forests and lead to reduced air quality. Additionally, the different structure of oil palm plantations compared to forest leads to different local microclimatic conditions resulting in higher temperature in oil palm plantations compared to forest.

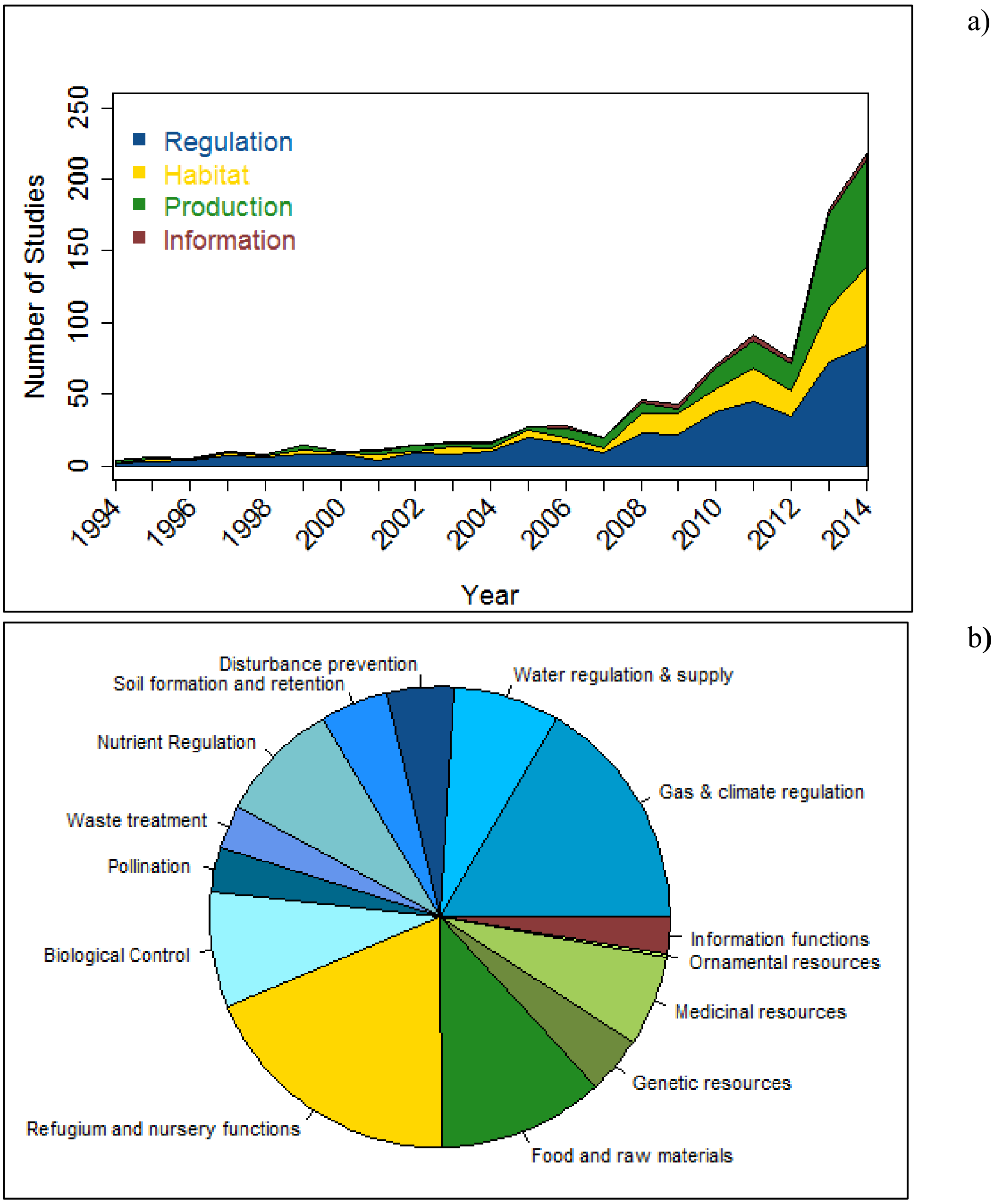

Fig. 4. (a) The number of studies on ecosystem functions in oil palm plantations increased over time, especially for regulation, habitat, and production functions. Only data from 1994 – 2014 are shown. (b) *Gas & climate regulation* and *Refugium & nursery functions* were the most studies ecosystem functions, while *Ornamental resources* were the least studied. Note that a paper may discuss more than one ecosystem function. Therefore, the sum of all categories is greater than the number of studies published.

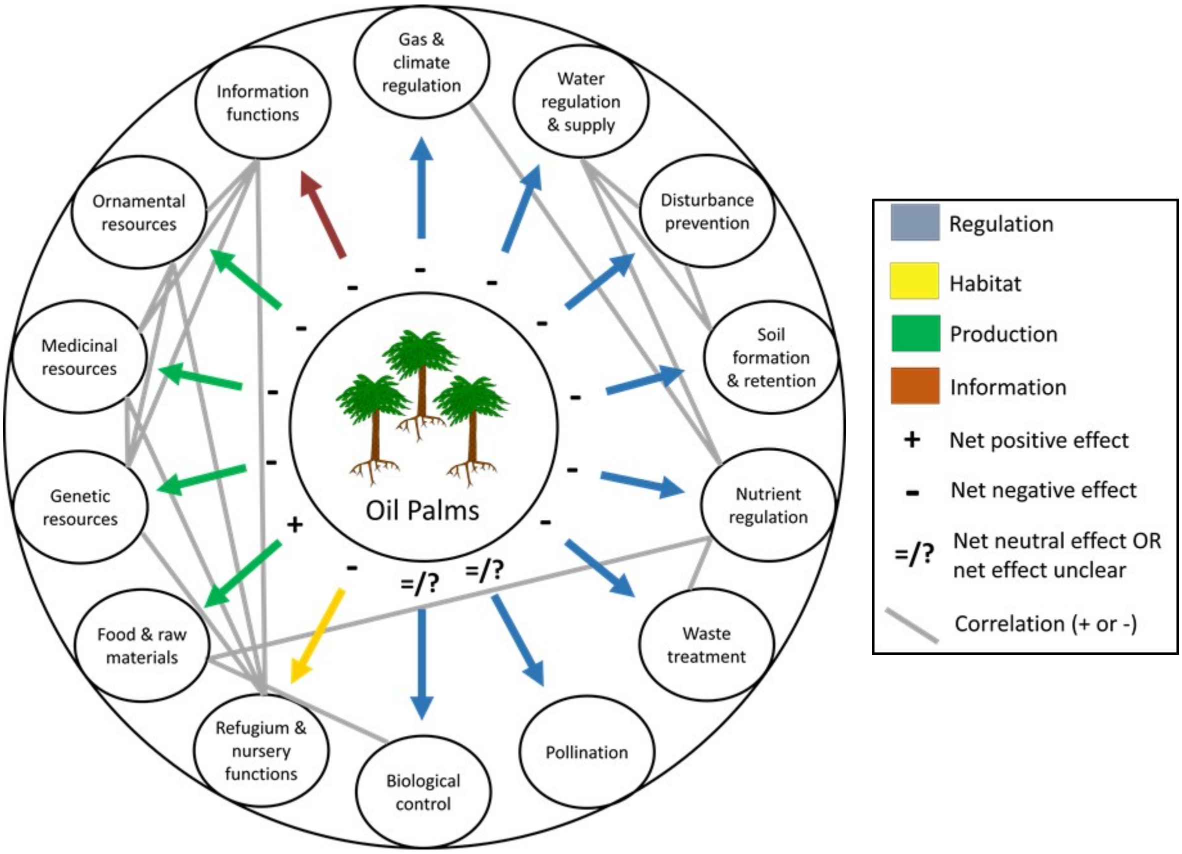

Fig. 5. Oil palms have a predominantly net negative effect on ecosystem functions when compared to primary and secondary rainforest. Net effects do not imply that all effects on a given ecosystem function are positive or negative, but that the majority or most dominant effects are in the given direction. See Table 3 for additional details with greater resolution. Estimates of net effect direction and correlation are qualitative based on the summary presented in this review.

Greenhouse gas fluxes

Net GHG fluxes depend on the balance between GHG uptake and release as a result of processes taking place above and below ground. Quantifying the overall effect of land-use changes from forest to oil palm plantation requires integrating across all different stages of the land-use change including land clearing, peat drainage and young oil palm stages and typically results in lower carbon stored and a negative GHG balance compared to forests. Carbon dioxide (CO_2) is the main GHG contributing to the GHG budget of oil palm plantations, while nitrous oxide (N_2O) and methane (CH_4) emissions are modest in comparison to CO_2 (Ishizuka et al. 2005, Jauhiainen et al. 2012, Melling et al. 2005 a,b, 2007 but see Hooijer et al. 2010), despite their greater global warming potentials (298 and 25 CO_2eq per molecule of N_2O and CH_4 respectively, IPCC 2007). CO_2eq (CO_2 equivalent) is the amount of CO_2 with the same global warming potential as the GHG, when integrated over a specified timescale (typically 100 years).

Land-clearing fires also lead to large releases of CO_2, both from vegetation and soil (Fargione et al. 2008). While a small fraction of the carbon in burned vegetation ends up stored long-term as biochar/charcoal, most is released. The conversion of forest on mineral soil to oil palm plantation results in carbon losses of 702 ± 183 Mg CO_2 ha^{-1} over 30 years (Fargione et al. 2010), while conversion on peatlands lead to carbon losses of 1486 ± 183 Mg CO_2 ha^{-1} to 3452 ± 1294 Mg CO_2 ha^{-1} over 25 or 30 years respectively (Murdiyarso et al. 2010, Fargione et al. 2010). Carbon dioxide emissions from burning soils are particularly large on peat. The emissions from peat fires for Indonesia during the fire events of 1997 have been estimated to be 0.81 to 2.57 Gt C (Page et al. 2002). Fires can also indirectly increase emissions by exposing organic-rich soil layers to rapid decomposition (Ali et al. 2006) and producing ash, which speeds peat decomposition (Murayama and Bakar 1996).

Large amounts of CO_2 are released when peat soils are drained to establish plantations and thus allowed to oxidize and decompose - estimates range from 26 to 146 t CO_2 ha^{-1} yr^{-1} (Schrier-Uijl et al. 2013). These estimates vary because the rate of CO_2 emissions depends on drainage depth and changes with time since drainage. Each additional 10 cm of drainage increases CO_2 emissions by approximately 9 Mg CO_2 ha^{-1} yr^{-1} (Couwenberg et al. 2010, Hooijer et al. 2010). The rate of CO_2 release from peat oxidation peaks immediately after drainage (the initial rate may be as high as 178 Mg CO_2 ha^{-1} yr^{-1} in the first 5 years (Hooijer et al. 2012) and then decreases with time. Considering all these variables, the most robust currently available empirical estimate for CO_2 emissions from peat drainage is 86 Mg CO_2 ha^{-1} yr^{-1}, calculated for a typical drainage depth of 60 – 85 cm, annualized over 50 years, and including the initial emission peak just after drainage (Page et al. 2011a). In addition, dissolved organic matter is flushed out of peat soils when they are drained, which then decomposes and releases additional CO_2 (Schrier-Uijl et al. 2013). This additional carbon loss is estimated to increase total carbon losses by up to 22% (Moore *et al*. 2013).

Oil palm plantations usually store less carbon in the soil than forests (Aweto 1995, Sommer et al. 2000, Ishizuka et al. 2005, Guillaume et al. 2015) even if some studies have reported similar carbon stocks in both land use systems (Tanaka et al. 2009, Frazão et al. 2013). The generally observed lower soil carbon storage in oil palm plantations results from increased decomposition in young plantations as a consequence of soil disturbance and increased temperatures (Aweto 1995, Sommer et al. 2000), decreased leaf litter input (Lamade and Boillet 2005), and increased soil respiration (Melling et al. 2005a, Lamade and Boillet 2005, Ishizuka et al. 2005). However, the extent of loss of soil carbon seems to depend on initial levels, with little loss in soils that are already carbon-poor (Smith et al. 2012). The difference between forests and oil palm plantations also decreases in the first decade or so after plantation establishment as organic matter is added to the soil by leaf litter and roots (Haron et al. 1998, Smith et al. 2012), but even when soil carbon reaches an equilibrium, it is only 55-65% of forest soil carbon levels (Lamade and Boillet 2005).

Oil palm plantations, like any vegetation, assimilate CO_2 from the atmosphere, acting as a carbon sink. Moreover, oil palm plantations assimilate more CO_2 and produce more biomass per hectare each year than forests due to very high fruit production (Lamade and Boillet

2005, Kotowska et al. 2015). This is often used as an argument in favor of oil palm agriculture. However, unless very long timescales are considered, this higher rate of carbon sequestration does not make up for the carbon released when forests are cleared for oil palm agriculture, as forests have more aboveground biomass than oil palm plantations (Germer and Sauerborn, 2008, Ziegler et al., 2012) - about 250 Mg CO_2 ha^{-1} compared to 25-90 Mg CO_2 ha^{-1} (Tomich et al. 2002; Bruun et al. 2009; Murdiyarso et al. 2010).

Oil palm plantations also release more N_2O from the soil into the atmosphere than forests. This is mainly the result of nitrogen (N) fertilizer use, and thus depends on how much fertilizer is applied (Murdiyarso et al. 2002, Schrier-Uijl et al. 2013). Fertilization rates in oil palm can vary between 100-300 kg N ha^{-1} yr^{-1} (Caliman et al. 2002; Chew 1995, Euler et al., *unpubl. data*) and therefore the N_2O emission rates are also highly variable and the magnitude of N_2O emissions in relation to CO_2 remains unclear (Murdiyarso et al. 2010). Additionally, a great spatial variability in N_2O emissions is observed due to fertilization being usually applied around the oil palms and not homogeneously over the plantations (Fowler et al. 2011). Nitrogen-fixing legumes planted as ground cover, especially in young oil palm plantations, may also contribute to N_2O emissions (Ishizuka et al. 2005). Nitrous oxide fluxes can also vary greatly with plantation age: Ishizuka et al. (2005) found higher N_2O emissions in young oil palm plantations compared to forest, but old plantations had lower emissions. Nevertheless, most studies so far have measured N_2O emissions in oil palm plantations that were 1.25 to 78 times higher than emissions from comparable forests (Murdiyarso et al. 2002, Fowler et al., 2011, Melling et al., 2007).

Methane emission from oil palm plantations and their controlling factors are highly variable depending on their establishment on mineral soils or on peatlands. The conversion of peatland primary forest to oil palm plantation could promote CH_4 oxidation and thus CH_4 uptake (Melling et al., 2005b) while on mineral soils this conversion has been shown to reduce the CH_4 uptake (Hassler et al. *unpubl. data*). Methane emissions from tropical peat soils depend on water table, temperature and litter characteristics and are generally low compared to temperate peat soils (Couwenberg et al. 2010). They make up less than 10% in terms of CO_{2eq} of the total emissions (Page et al. 2011a). On mineral soils, Fowler et al. (2011) and Ishizuka et al. (2005) found only small fluxes of methane both in forest and oil palm plantations.

Air quality

Oil palm plantations affect local and regional air quality in two ways: air pollution from land clearing fires, and increased emissions of volatile organic compounds (VOC).

Land clearing fires can lead to severe smoke and haze pollution, especially in dry years. For example, during the El Niño episodes in 1994 and 1997, fires in Southeast Asia led to tremendous air pollution with severe negative impacts on human health (Murdiyarso et al. 2002; Glover and Jessup 2006). Forest fires release carcinogens and toxic gases such as carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2) and particulate matter (PM), decreasing air quality (Reddington et al. 2014) and causing immediate respiratory problems

(Mott et al., 2005) as well as long-term health problems (Ostermann and Brauer 2001; Kamphuis et al. 2010, Schrier-Uijl et al. 2013) or increasing mortality (Johnston et al. 2012). In addition, fires add black carbon to the atmosphere, which might additionally enforce global warming (Fargione et al. 2010).

Oil palms are a major emitter of isoprene (Misztal et al. 2011) and in general produce more VOC than forests (Fowler et al. 2011). While the relationships between VOC concentrations and atmospheric chemistry and climate are still poorly understood (Wilkinson et al. 2006), isoprene and other VOC emissions from oil palm plantations are generally expected to decrease surrounding air quality (Royal Society 2008; Pyle et al. 2011). This is because isoprene can lead to the production of aerosols/haze and ozone, especially in areas where nitric oxide (NO_x) concentrations are high (e.g., where there is a lot of vehicle traffic; Sheil et al. 2009, Fowler et al. 2011, Pyle et al. 2011). In studies so far, similar ozone concentrations have been measured in the boundary layers of forests and oil palm plantations (Hewitt et al. 2009, 2011). However, future increases in NO_x concentrations due to fertilization and industrialization might lead to critical increases of ozone concentration in oil palm plantations (Hewitt et al. 2009, 2011) and negative impacts on human health, crop yields, and global climate (Royal Society 2008). Thereby, the emission of VOCs from oil palm plantation indirectly affects regional and global climate (Misztal et al. 2011).

Local climate

Oil palm plantations are expected to affect global climate through GHG emissions, but they also have a direct effect on local microclimates. Oil palm plantations have lower, less dense canopies and a lower leaf area index than forests, and as a result are warmer and drier. A recent study in Borneo found that mean maximum air temperatures were up to 6.5 degrees C warmer in oil palm plantations than in primary forests, and up to 4 degrees C warmer in oil palm plantations than in logged forests, with similarly large differences in air moisture content and soil temperature (Hardwick et al. 2015). This effect is expected to be more pronounced in young compared to oil palm plantations because of the even lower canopy cover and lower leaf area index in the young oil palm plantation.

Mitigation

The most effective possible action to reduce GHG emissions related to oil palm agriculture is to limit oil palm expansion to areas with moderate or low carbon stocks. Specifically, this would require stopping the development of new plantations on peat land as peat oxidation and peat fires are the largest oil palm-related GHG sources. and extending the current moratorium on new concessions in primary forests (Austin et al. 2015). Rehabilitation and restoration of converted peatlands is also an option (Schrier-Uijl et al. 2013). In existing peatland plantations, emissions can be minimized by keeping the water table as high as possible (Hooijer et al. 2010, Othman et al. 2011) or rewetting (Couwenberg et al. 2010), by maintaining ground cover to reduce soil temperature and decomposition rates (Hooijer et al. 2012, Jauhiainen et al. 2012), and possibly by compacting the peat soil before planting to reduce oxidation and decomposition (Schrier-Uijl et al. 2013). Maintaining a hydrological buffer zone around plantations helps minimize emissions from neighboring undeveloped peatlands (Page et al. 2011b).

Other possible actions to reduce GHG emissions from oil palm plantations include limiting flooding in plantations, reducing nitrogen fertilizer use, and limiting the use of fire for clearing. Flooding should be avoided because it leads to increased methane emissions (Schrier-Uijl et al. 2013). The need for nitrogen fertilizers can be reduced by using composted plantation and mill wastes instead, by timing fertilizer application to minimize the amount washed away by rains, and by using slow-release coated fertilizers (Schrier-Uijl et al. 2013). Finally, as mentioned in the introduction, land-clearing fires continue to be used even though they have been outlawed in Malaysia and Indonesia, and it is unclear how their use could be eliminated entirely. At the very least, limiting the area that is burned in a day would help minimize the air pollution impact (ECD 2002).

Research gaps

The best available estimates of gas fluxes from oil palm plantations are largely based on few measurements from short term studies using mostly measurement techniques which are not always representative of the whole ecosystem (i.e. using chamber measurements which only consider soil GHG fluxes and not whole-ecosystem fluxes, and with not enough replicates to cover for soil heterogeneity). There is a great need for larger studies, over longer time periods, with more measurements, comparing a wider range of environments and management practices, and using more rigorous methods (Lamade and Boillet 2005; Schrier-Uijl et al. 2013). In addition, more data is needed on soil carbon, the role of ground cover plants, emissions from drainage canals and ponds in plantations, and on methane and N_2O emissions (Lamade and Boillet 2005; Schrier-Uijl et al. 2013). Locally, the biophysical changes (e.g., albedo, surface energy fluxes, microclimate) associated with changes in land use are important drivers of climate, but have received much less research attention

(b) Water regulation & supply

Water regulation and supply refers to the amount, timing, and quality of water stored in and flowing through and out of an ecosystem (Millennium Ecosystem Assessment 2005). The conversion of forest to oil palm plantation generally leads to a decrease in water storage, an increase in annual yield, and a decrease in water quality, but these changes tend to become less extreme as plantations mature (Comte et al. 2012) and can be reduced to some extent with management (Yusop et al. 2007).

Water storage and supply

Water storage in oil palm plantations may be reduced in two ways: peatland drainage and through decreased water infiltration. Peatlands are like giant sponges, holding large quantities of water. Drained peat is inevitably lost, either quickly to fire or slowly to oxidation, permanently reducing the size of the "sponge" and the area’s water storage capacity (Andriesse 1988). Soil compaction in oil palm plantations reduces the rate at which rainfall infiltrates into the soil (Rieley 2007), leading to surface runoff and reducing groundwater recharge (Gregory et al. 2006). Oil palm plantations also have much higher annual water yields than forests (the total amount of water flowing out) and may have higher variability in water yield if soil infiltration rates have been reduced (Bruijnzeel 2004). The difference in water yield between plantations and forests can be extreme (e.g., 270-420% increase in Malaysia, DID 1989). Water yield is increased through a decrease in evapotranspiration (Rieley 2007, Ellison et al. 2012) and reduced infiltration rates (Gregory et al. 2006, Rieley 2007). While overall water yield is increased, baseflow (streamflow coming from groundwater) is decreased. For example, baseflow accounted for 54% of streamflow in oil palm plantations but 70% of streamflow forest (Abdul Rahim and Harding 1992). This may result in greater variability in water yield on oil palm plantations.

Differences in evapotranspiration rates are strongest in young palm plantations, and become more similar in mature plantations (1000−1300 mm yr^{-1} for oil palms versus 1000-1800 mm yr^{-1} for lowland forests, Bruijnzeel 2004, Comte et al. 2012). Infiltration rates are lowered through soil compaction (e.g., due to land clearing or traffic, Bruijnzeel 2004, Banabas et al. 2008). Reduced infiltration leads to amplified catchment response to rainfall events, e.g. increased peak discharge and decreased time-to-peak (DID 1989, Bruijnzeel 2004). This means that, even though total annual streamflow coming from oil palm plantations is usually greater, streamflow in dry seasons, when groundwater is the main water source, is likely to be lower (Bruijnzeel 2004, Anderson 2008, Adnan and Atkinson 2011). To summarize, water supply from oil palm plantations is less constant and dependable than the water supply from forests.

Water quality

Sediment runoff is one of the largest water quality problems in and around oil palm plantations, as it is greatly increased by the decreased ground cover and increased surface runoff in plantations. For example, in one study, sediment loads increased from below 50 Mg km^{-2} yr^{-1} in forest to 400 Mg km^{-2} yr^{-1} immediately after clearance (DID 1989). The establishment of ground cover decreases this impact but sediment loads in water bodies remain higher than in forest - in the DID study (1989), sediment loads dropped only to 100 Mg km^{-2} yr^{-1} after the legume cover was established. This soil loss can be a severe threat to aquatic ecosystems (Edinger et al. 1998, Bilotta and Brazier 2008, Buschman et al. 2012).

Drainage of peat soils for plantation establishment also has consequences for water quality. Some peat soils occur above acid sulphate soils. As the drained peat subsides or is lost to oxidation, these lower layers are exposed to oxygen. As they oxidize, they increase soil acidity, which may affect water quality in the surrounding area (Wösten et al. 1997). In addition, peat drainage reduces the ability of peatlands to act as a freshwater buffer, allowing salt water to intrude (Silvius and Giesen 1992 cited by Silvius et al. 2000).

Finally there is the impact of oil palm production itself. Fertilizers, pesticides, and herbicides are inevitably washed away, contributing to eutrophication of water bodies and negatively affecting aquatic organisms (Bilotta and Brazier 2008, Kemp et al. 2011, Gharibreza et al.

2013). In addition, streams and rivers near oil palm mills are often contaminated with POME due to leaks (Ahmad et al. 2003, Wakker 2005). POME has also been shown to have negative effects on aquatic ecosystems (e.g., Olaleye and Adedeji 2005).

Mitigation

The negative impacts of peatland drainage are likely to be irreversible (Comte et al. 2012). As for gas and climate regulation, the best option from an ecosystem function perspective is to completely avoid draining peat (Comte et al. 2012). In existing plantations, management practices can help improve water regulation and supply. Herbaceous ground cover, mulch made of plantation wastes such as empty fruit bunches, and palm fronds stacked across slopes all help to slow runoff, increase infiltration, and increase groundwater recharge (DID 1989, Fairhurst 1996, Banabas et al. 2008). Buffer zones of natural vegetation along streams filter runoff and improve water quality (ECD 2002). Leguminous ground cover and mulch also reduce the need for fertilizer application (e.g., Agamuthu and Broughton 1985). Nutrient models, guidelines, and foliar sampling and analysis also reduce the need for fertilizers by maximizing the efficiency of fertilizers used (Comte et al. 2012). Pesticides can be replaced by biological pest control (Yusoff and Hansen 2007) and herbicides can be replaced by manual weeding (ECD 2002). Finally, silt-pits and foothill drains can be built to trap sediment from surface runoff and prevent it from entering streams (Comte et al. 2012).

Research gaps

Water regulation in oil palm plantations is a topic of active research (e.g., Fig. 6). There is a need for studies identifying actual water management practices in plantations (Comte et al. 2012), investigating the impact of pesticides in water bodies (Comte et al. 2012), and assessing whether nutrient leaching is still a problem when organic fertilizers are used (Okwute and Isu 2007). Another research priority is to determine methods of restoring dry-season water flow (Bruijnzeel 2004).

(c) Disturbance prevention

Disturbance prevention is defined as the ability of an ecosystem to prevent and mitigate disruptive natural events (de Groot et al. 2002). Most of the studies we found examined the disturbance prevention ability of agricultural areas in general and not oil palm plantations in particular. The majority of studies investigated floods, droughts, and landslides; only a few studies addressed wildfires. Risks of flooding, drought, landslides, and wildfires are all higher in oil palm plantations and surrounding areas than in forests and their surroundings.

Fig. 6. On-going research includes measurement of water interception by oil palms. Photograph by Suria Tarigan.

Flooding & Drought

As discussed in section *III. 1b. Water regulation & supply: water storage and supply*, water outflow from oil palm plantations as compared to forests is increased when there is rain and decreased during dry times. This means that both floods and droughts are more likely in areas downstream of oil palm plantations than areas downstream of forests (Rieley and Page 1997, Bruijnzeel 2004, Bradshaw et al. 2007, Rieley 2007). The magnitude of the difference in flood/drought likelihoods before and after plantation establishment depends on the hydraulic conductivity before land conversion - plantation establishment will cause the greatest difference in cases where the previous landscape was very effective at preventing droughts/floods (Gilmour 1977).

The risk of flooding is increased downstream of oil palm plantations because water yields are increased (Adnan and Atkinson 2011) because soil compaction causes an increase in surface runoff, leading to increased peakflows and stormflows (DID 1989, Jusoff 1991, Van der Plas and Bruijnzeel 1993, Bruijnzeel 2004), and because peat drainage for plantation establishment reduces the size of the peatland water reservoir and its ability to buffer water outflow rates (Clark et al. 2002, Rieley 2007, Tan et al. 2009). In addition, soil subsidence due to peat oxidation or burning can lower the soil surface enough that the water table can rise above it during periods of high rainfall, causing floods directly (Page et al. 2009).

The risk of drought is increased downstream of oil palm plantations because more rainfall goes directly into streams, and less into groundwater (Rieley and Page 1997, Rieley 2007), and because peatland drainage for plantation establishment reduces the size of the peatland water reservoir and its ability to supply water during dry periods (Clark et al. 2002, Rieley 2007, Tan et al. 2009).

Landslides
The establishment of oil palm plantations is likely to increase the likelihood of shallow landslides; large, deep landslides (>3m soil depth) are mostly influenced by geological, topographic, and climatic factors and should not be affected by land use (Ramsay 1987a, 1987b, Bruijnzeel 2004). It is known that forests reduce the probability of shallow landslides by stabilizing the top meters of soil with their roots (Starkel 1972, O'Loughlin 1984), and that deforestation increases the risk of landslides on steep terrain (Imaizumi et al. 2008, Walsh et al. 2011). In addition, soil stability is generally lower in plantations and agricultural land because there is less ground cover and soil structure than in forests (Sidle et al. 2006). Thus, the risk of shallow landslides should increase in oil palm plantations, particularly young plantations. However, we found no direct data to confirm or reject this prediction.

Wildfires
The establishment of oil palm plantations increases the risk of wildfires and wildfire frequencies in surrounding areas in many ways (Hope et al. 2005, Naidoo et al. 2009). First, despite laws banning land clearing fires in Malaysia and Indonesia, fire is still often used to clear vegetation for the establishment of oil palm (Page et al. 2011a), greatly increasing the risk of accidentally starting a wildfire. Second, peat that has been drained for plantation establishment is very flammable due to its high content of organic matter and flammable resins (Mackie 1984). Peat fires can burn underground, making them difficult to extinguish. Third, oil palm plantations are in general more flammable than forests, which usually can burn only during times of moisture stress (Cochrane 2003). This is because oil palm plantations are drier and more open than forests (Mackie 1984, Leighton and Wirawan 1986, Gascon et al. 2000, Aiken 2004, Hardwick et al. 2015). Finally, the establishment of oil palm plantations tends to lead to degradation of surrounding forests and an increase in human activities that can start wildfires (Sheil et al. 2009), while roads can also offer a highway for fire spreading (Mackie 1984).

Mitigation
The strategies for reducing the risk of natural disturbances in and around oil palm plantations are quite straightforward. The measures described in section *III. 1b. Water supply & regulation: mitigation* to increase infiltration and groundwater recharge (ground cover, mulch, and stacking palm fronds across slopes) will also help prevent floods and droughts. Avoiding draining peatlands, or draining them as shallowly as possible, helps reduce the risks of floods, droughts, and fires. To prevent landslides, Walsh et al. (2011) suggest to

leave areas with slopes >25% with their natural forest cover intact. Finally, fire should not be used to clear land for establishing new plantations.

Research gaps
We did not find any studies directly addressing the risks of landslides or wildfires in or around oil palm plantations. Further study of water dynamics in mature oil palm plantations is needed as well, as it is unknown if they show the same differences from forest as young plantations (Comte et al. 2012). Drought risks due to meso-climate need to be studied in the context of oil palms as well.

(d) Soil formation & retention

Here, we use an ecosystem functions framework, and define soil formation as the weathering of rock, accumulation of organic matter, and horizon formation through transformations and/or translocation processes, whereas soil retention refers to the role of soil biota (including vegetation root matrix) and slope morphological and positional attributes in preventing soil erosion (modified from de Groot et al. 2002). As soil formation takes place on the scale of centuries (Pimentel and Wilson 1997), and oil palm plantations are of recent establishment, we did not find any studies examining the role of oil palm plantations in long-term soil formation relative to the original land use (e.g., tropical forests, see Fig. 7 for an example of an Acrisol soil profile (FAO classification) in an oil palm plantation converted from a lowland tropical forest). Most of the studies we found address soil loss, which is increased in oil palm plantations, especially during land clearing and establishment.

Fig. 7. A soil profile from an oil palm plantation in Jambi, Indonesia. Photo by Oliver van Straaten, 2010.

Soil retention

As discussed in the sections on water regulation and disturbance prevention, soil retention is decreased in oil palm plantations compared to forests because oil palm plantations have less ground cover, weaker root systems, and more surface runoff. Natural forests have very low annual sediment losses (<1 - 2 Mg ha^{-1}, Hartemink 2006, Buschman et al. 2012). Based on estimates from erosion models, one can expect soil loss from oil palm plantations to be about 50 times higher (Buschman et al. 2012). Several other soil erosion studies in oil palm catchments in Malaysia have found similar results (e.g., see Hartemink 2006).

Most soil losses occur during plantation establishment (Fig. 2a), when land is bare and maximally exposed to wind and water erosion (DID 1989, Bruijnzeel 1990, 2004, Douglas 1999, Hartemink 2005). The erosion models of Buschman et al. (2012) predict that soil loss from bare ground could be 200 times higher than soil loss from primary forest, and soil loss from bare hillsides could be as much as 10,000 times higher than soil loss from forested hillsides (Besler 1987). In addition, land-clearing fires can cause soil hydrophobicity, increasing surface runoff and soil erosion (Sidle et al. 2006), and large amounts of soil are lost through oxidation after peat drainage (Schrier-Uijl et al. 2013). Rates of soil erosion should then decrease with plantation age, as the oil palm canopy closes and root network develops (Fig. 2b), although even in mature plantations the canopy is broken by roads (Fig. 2c) and other infrastructure (Hartemink 2005).

Mitigation

A number of different options exist for reducing soil erosion in oil palm plantations. Terraces are often built to reduce soil erosion in steep areas, but for these to be effective they must be well planned, correctly constructed, and properly maintained (Dorren and Rey 2004). Lim (1988), for example, measured high soil loss rates in terraced oil palm plantations (>20 Mg ha^{-1} yr^{-1}). Therefore, terraces must be adapted to local conditions and combined with additional soil conservation practices. Alternatively, sloped areas and other areas with easily eroded soil can be left as forest (ECD 2002). Another commonly used management practice that improves soil retention is mulching with pruned palm fronds (Fig. 8) or EFB. Maene et al. (1979) found a three-fold reduction in soil loss in a plantations with mulched paths compared to a plantation with uncovered paths. Ground cover vegetation also reduces soil erosion (DID 1989, ECD 2002). Finally, soil erosion can be minimized by good planning before and during plantation establishment, so that soils are only left bare for as little time as possible (ECD 2002).

Research gaps

Soil erosion and sedimentation model predictions (e.g., LAPSUS or LandscApe ProcessS modelling at mUlti dimensions and scaleS Schoorl et al. 2000, 2002, Schoorl and Veldkamp 2001) could be tested in the field, with a particular emphasis on potential differences between landscape configurations, practices, and field sizes.

Fig. 8. An example of a mature oil palm plantation where oil palm fronds are used as a mulch. (Jambi, Indonesia, photo by Oliver van Straaten, 2010).

(e) Nutrient regulation

Nutrient regulation refers to the upkeep of nutrient cycles and the provision of sufficient nutrients for plant growth. In the original forest ecosystems, prior to their conversion to oil palm plantations, their high ecosystem productivity is sustained even if they are on highly weathered, nutrient poor soils because of efficient cycling of rock-derived nutrients (phosphorus (P) and base cations) between vegetation and soil as well as their inherently high biological nitrogen (N) fixation (Hedin et al. 2009). This efficient cycling of nutrients between plants and soil is altered when tropical forests are converted to agricultural land-use systems, resulting in a decrease in soil fertility (Ngoze et al. 2008). The large amounts of nutrients previously bound in the vegetation and soil organic matter are released in a pulse from burning of slashed vegetation and are susceptible to losses through leaching and gaseous emission (Mackensen et al. 1996, Dechert et al. 2005). Such losses are especially high in the earlier years of crop establishment and decrease with time (Klinge et al. 2004), and the magnitude of decrease in soil fertility depends on the initial soil fertility of the original forest (Dechert et al. 2004). Additionally, in fertilized land-use systems, like oil palm plantations, the eventual decline in soil fertility with age of conversion is abated although nutrient leaching losses are sustained (Allen et al. *unpubl. data*, Kurniawan et al. *unpubl. data*). Management practices in oil palm plantations include fertilizer addition, liming, and occasionally mulching with compost).

Nutrient losses

Large amounts of nutrients are lost from oil palm plantations, through the harvest and removal of palm biomass (Hartemink 2005) and leaching (Goh and Härdter 2003). Large amounts are also lost during plantation establishment as a result of forest clearing and the increased soil leaching that follows (DID 1989, Brouwer and Riezebos 1998). In Jambi, Sumatra, Indonesia, where rapid conversion of forest to oil palm is occurring, drainage leaching fluxes at 1.5-m soil depth (which is well below the rooting depth) of dissolved organic carbon, sodium, calcium, magnesium, and total aluminum increased under oil palm plantations compared to the original forests (Kurniawan et al. *unpubl. data*). Depending on how and when fertilizers are applied, and plantation age, up to 10% of what is applied can be lost due to runoff (Maene et al. 1979, cited in Goh et al. 2003) and drainage leaching leading to detrimental effects on water quality (see *section III. 1b. Water regulation & supply: Water quality*).

Nutrient inputs

The main nutrient inputs in oil palm plantations are fertilizers, lime, nitrogen-fixing ground cover, and compost/mulch. Large quantities of mineral fertilizers are used in oil palm plantations (Sheil et al. 2009). Leguminous plants are commonly planted as a cover and can contribute 239 kg N ha^{-1} yr^{-1} (Agamuthu and Broughton 1985). However, this ground cover dies off when the canopy closes, releasing a large quantity of N that is vulnerable to leaching (Campiglia et al. 2011). EFB, POME, male inflorescences, and fronds can all be used for mulch or compost, which gradually breaks down and releases nutrients into the soil (Comte et al. 2012). One study found that oil palms in a plantation in Sumatra produced 10 Mg of dry palm fronds per hectare, containing 125 kg N, 10 kg P, 147 kg K, and 15 kg Mg (Fairhurst 1996).

Mitigation

Unlike mineral fertilizers and leguminous cover crops, mulch/compost releases nutrients slowly and may have minimal risk of nutrient loss to drainage leaching or runoff. Mulching with compost could be practiced in more plantations, especially smallholder plantations, to improve soil nutrient balances (Comte et al. 2012). More careful planning of fertilizer application, taking into account site characteristics, rainfall timing, and crop requirements, would also help minimize nutrient losses via fertilizer runoff (Goh et al. 2003).

Research gaps

More empirical data are needed on nutrient retention and nutrient use efficiencies in oil palm plantations. Such data will not only provide information on yield but also on the associated environmental consequences, and thus are useful tools to inform large-scale plantation managers, policy makers, agricultural extension workers and smallholders. In general, studies are needed to test management trials on-site for screening management practices (e.g., mulching with compost, organic fertilization, various rates of chemical fertilization, weed control) that will yield optimum benefits (e.g., yield and profit) with maximum nutrient retention efficiency (or less nutrient losses) in the soil. Economic evaluation should also be conducted on such management trials to select for the optimal N, P, and base cation input requirements for achieving and sustaining profitable crop production while preventing degradation in soil fertility. In particular, field studies on decomposition rates and nutrient release from frond stacks, or piles of senesced fronds put on inter-rows to facilitate harvest and maintenance works, are lacking even if such practice is commonly done in both smallholder and large-scale plantations. Information on nutrient contributions and losses from frond stacks will provide the first evidence of whether spreading fronds on the whole area rather than stacking them on a narrow strip can be beneficial in abating nutrient decline. Presently, there are on-going studies directly comparing soil nutrient levels and leaching losses in forest and oil palm plantations using a space-for-time substitution approach (M. D. Corre, *pers. observ.*).

(f) Waste treatment

Waste treatment refers to the ability of an ecosystem to remove or recycle organic or inorganic waste. Palm oil production results in large amounts of organic waste, in particular EFB and POME (Igwe and Onyegbado 2007, Stichnothe and Schuchardt 2010). While there are many studies on the technical aspects of waste treatment, we did not include these in the database in order to focus on those studies relating to the ecosystem functioning aspects of waste treatment. As discussed in section *III. 1b. Water regulation & supply: Water quality*, oil palm plantations may act as net sources of organic waste to the surrounding environment. The only study so far to compare litter decomposition rates (organic waste treatment) between oil palm plantations and forests found no difference (Foster et al. 2011). Hypothetically, the rate of decomposition of organic matter may differ between forests and oil palm plantations as oil palm plantations are on average warmer and drier than forests (Hardwick et al. 2015), and they are expected to have lower biodiversity and abundance of decomposing organisms (Foster et al. 2011). However, the direction of expected change is unclear, as drier conditions should slow decomposition (Lamade and Boillet 2005), while warmer conditions should speed decomposition (Aweto 1995, Sommer et al. 2000). Organic wastes from oil palms can be used to treat a variety of pollutants, including heavy metal pollution (e.g., Ahmad et al. 2011, Vakili et al. 2014).

Mitigation

Organic wastes from palm oil production can be recycled in oil palm plantations into mulch and compost (Oviasogie et al. 2010, Stichnothe and Schuchardt 2010, Koura et al. 2015), or can be treated separately with the potential for additional biomass production (e.g., Darajeh et al. 2014, Hayawin et al. 2014). Understory vegetation can help to maintain the abundance and species richness of understory beetles in oil palm plantations (Chung et al. 2000) and therefore may improve decomposition rates of organic matter in oil palm plantations. Understory cover may also slow undesirable peat decomposition through a reduction in soil temperature (Hooijer et al. 2012, Jauhiainen et al. 2012).

Research gaps
There is a clear need for studies of overall waste treatment differences between oil palm plantations and forests, including comparison of net production (or removal) of organic and inorganic wastes at the plantation and in the surrounding environment.

(g) Pollination

The ecosystem function pollination refers to both the pollination of crops and wild plants and influences the production of 70% of the 124 globally most important crops, 35% of global food supply, and is required by 88% of all plant species (Klein et al. 2007, Ollerton et al. 2011). We found only 31 papers relevant to this ecosystem function in oil palm plantations (Table 2, Fig. 4b). The data available are too incomplete to come to any conclusion about differences in pollination between forests and oil palm plantations.

Native pollinators
Compared to forests, oil palm plantations support fewer invertebrate species (Sodhi et al. 2010) and lower abundances of pollinating bees, while Liow et al. (2001) found a greater diversity of bees. However, the data of Liow et al. (2001) come from observations along transects of only the lower canopy and shrub layers and may not hold for higher canopy layers.

Pollination by Elaeidobius *weevils*
In their native range, oil palms are pollinated mainly by *Elaeidobius* weevils (Vaknin 2012). Because oil palm yields are dramatically lower without these weevils (Greathead 1983, cited by Foster et al. 2011), *Elaeidobius kamerunicus* has been introduced into South America and Southeast Asia (Vaknin 2012). *Elaeidobius* weevils also pollinate other palm species such as betelnut (*Areca catechu*) and coconut (*Cocos nucifera*), and so in theory, oil palm plantations may thus provide pollination functions to neighboring crops.

Mitigation
The oil palm industry's reliance in most regions on a single pollinator species, *Elaeidobius kamerunicus*, is risky. One way to address this would be to introduce additional *Elaeidobius* species, but this carries the usual risks of exotic species introduction (Foster et al. 2011). Alternatively, plantation managers could implement measures to increase insect and bird diversity in oil palm plantations, such as increasing the height, coverage, and diversity of ground cover plants, planting additional tree species, and maintaining unplanted areas with native vegetation cover (Koh 2008b, Koh et al. 2009). This should improve pollination rates both of native plants and of oil palms, which can be pollinated also by native insects (Mayfield 2005, Foster et al. 2011).

Research gaps
Direct comparisons of pollination success rates in oil palm plantations and forest would be helpful in theory, but difficult to carry out in practice because of the drastically different plant communities and pollination systems in the two systems. The highest priority, then,

should be additional surveys of pollinator abundance and diversity (including insects, birds, and bats) in oil palm plantations and neighboring forests. It would also be useful to test whether oil palm plantations improve pollination of other neighboring palm crops, as predicted. Whether the fluctuations of oil palm fruit set and yield are driven by pollination limitation is still a matter of debate by Sumatra oil palm farmers (T. Tscharntke, *pers. observ.*)

(h) Biological control

An organism becomes an agricultural pest or a disease if it causes enough damage to a crop that is above the economic threshold level. The ecosystem function biological control refers to the ability of ecosystems to prevent organisms from acting as pests or diseases (Upadhyay et al. 2001, de Groot et al. 2002, Norris et al. 2003, Horowitz and Ishaaya 2004).

Biological control within oil palm plantations

In oil palm plantations, the main organisms that may act as pests or diseases include trunk borers, defoliators, frugivores, planthoppers, and wilt diseases. These species can be managed by biological control. Biological control in oil palm plantations and forests is qualitatively different. In general, tropical monoculture tree plantations are more susceptible to pest outbreaks than native forests (Nair 2001). This is likely a result of reduced species diversity and abundance of native parasitoids and predators of oil palm pests due to the landscape simplification (Tscharntke et al. 2007, Foster et al. 2011). The simplification of the biological and physiological environment creates unsuitable conditions for most biocontrol agents in the plantation because of a significant decrease in food and suitable habitat resources (Chung et al. 2000, Donald 2004, Koh 2008a, Bateman et al. 2009, Koh et al. 2009). For instance, insectivorous birds and bats, known as biocontrol agent for number of pests (Maas et al. 2013), have difficulty adapting to oil palm plantations, resulting in higher pest attacks, and reduced crop yield (Aratrakorn et al. 2006, Koh 2008a).

However, biological control in oil palm plantations is managed directly by plantation owners, who introduce and support species that combat oil palm pests and diseases (Wood 2002, Corley and Tinker 2003). These include a fungus and viruses to control the rhinoceros beetle *Oryctes monoceros* (Huger 2005, Murphy 2007), parasitoids to control planthoppers (Guerrieri et al. 2011, Gitau et al. 2011), *Trichoderma harzianum* (a fungus) and endophyte bacteria to control the *Ganoderma* fungus which causes basal stem rot (Susanto et al. 2005, Sundram et al. 2008, 2011, Suryanto et al. 2012), owls and snakes to control rats (Sheil et al. 2009), and adult assassin bugs to control a variety of herbivorous insects (Turner and Gillbanks 2003, cited in Foster et al. 2011).

Biological control in surrounding areas

The overall effect of oil palm plantations on biological control in surrounding areas is unclear. Because some oil palm pests also affect other crops, surrounding areas may benefit from the release of control agents for these pests in oil palm plantations. For instance, rhinoceros beetles and planthoppers are also pests of coconut (Huger 2005, Guerrieri et al.

2011, Gitau et al. 2011) and basal stem rot also affects the timber tree *Acacia mangium* (Eyles et al. 2008). In addition, oil palm products can be used for pest control: empty fruit bunches (EFB) can be used to combat rhinoceros beetles in coconut (Allou et al. 2006) and wet rot in okra (Siddiqui et al. 2008), endophytic bacteria isolated from oil palm roots can be used against *Fusarium* rot in Berangan banana (Fishal et al. 2010), and palm oil reduces beetle incidence in maize, sorghum, and wheat grains (Kumar and Okonronkwo 1991). However, oil palm plantations can also foster the spread of pests into surrounding areas. For example, one study showed that soil disturbance caused by wild pigs feeding in oil palm plantations correlated with the invasion of the exotic shrub *Climdemia hirta* into forest (Fujinuma and Harrison 2012). As oil palm plantations harbor high numbers of frugivorous birds (Kevin Darras, *unpubl. data*), frugivory may also be enhanced in adjacent habitats.

Mitigation

By definition, the use of integrated pest management practices instead of chemical spraying alone increases the provisioning of biological control in oil palm plantations. Management practices that increase diversity in oil palm plantations, especially arthropod and bird diversity (see section *III. 2a Refugium and nursery functions*), may also increase the provisioning of biological control - in the case of native insectivorous birds, at least, it is clear that they can significantly reduce herbivory of oil palms (Aratrakorn et al. 2006, Koh 2008a).

Research gaps

While much research has focused specifically on oil palm pests and diseases and methods for combatting them, little is known about the contribution of native biodiversity to biological control in oil palm plantations. It is necessary to study the habitat requirements of biological control agents and the potential for incorporating the necessary habitat features into oil palm plantations in order to maintain robust biological control agent populations. There is a need for basic surveys of biodiversity in oil palm plantations and comparable forests that identify naturally occurring pest control agents and measure their abundances. Further studies are needed on biocontrol, both in forests and oil palm plantations, in a range of conditions – similar to the approach taken by Koh (2008a). More research is needed on methods to maintain biological control agents in the landscape, such as the role of riparian buffers in the plantation, patches of semi-natural habitat within or surroundings plantations, and growing flowering plant in the understory. Spillover from crop fields to adjacent natural habitat or crops has been little studied, as most studies on spillover across habitat boundaries focus on effects of natural habitats on cropland (Blitzer et al. 2012).

(2) Habitat functions

(a) Refugium & nursery functions

These functions refer to the ability of an ecosystem to provide habitat that meets species' needs and thus allows them to survive and reproduce. These functions are thus crucial for the maintenance of biodiversity. While oil palm plantations do support some native species, it is clear that conversion of forest to oil palm is a major threat to biodiversity (Foster et al. 2011, Savilaakso et al. 2014).

Biodiversity supported by oil palm plantations

Oil palm plantations are not entirely homogeneous monocultures. They support some native plants in the ground cover layer, as epiphytes on oil palm trunks, and in unplanted areas, for instance on steep slopes and along waterways (Basiron 2007). However, most non-crop plants are pantropic weeds.

Within planted areas, despite general biodiversity losses compared to forest, some species thrive. Oil palm communities are dominated by generalist species (Fitzherbert et al. 2008). Bees have been found to have higher species richness in oil palm plantations than in forest (although in this study the forest presumably was undersampled; Liow et al. 2001), and dung beetles, isopods, lizards, and bats are more abundant (though less diverse; Foster et al. 2011). Vascular epiphytes, i.e. plants germinating and growing non-parasitically on other plants, are a conspicuous element of the vegetation in oil palm plantations. Depending on the plantation age and management (e.g., Luskin and Potts 2011, Krobbach 2014), epiphytes are ubiquitous and palm trunks are often covered by epiphytic ferns. Compared to forests, epiphyte abundance can be even higher in oil palm plantations and epiphyte diversity can reach similar levels (Böhnert et al. unpubl. data, Altenhövel 2013). Some epiphytes appear to profit from the frequent pruning of palm leaves and the decaying leaf bases that form humus pots. At the landscape scale, in contrast, there is a significant loss of epiphyte diversity in oil palm plantations compared to forests (Altenhövel 2013) caused by an almost complete absence of many specialized flowering plant groups such as orchids. However, there is evidence that some epiphytes such as the bird's nest fern (*Asplenium nidus*) play an important role in the maintenance of ant diversity (Fayle et al. 2010).

Biodiversity loss in oil palm plantations

Biodiversity is much lower in oil palm plantations than forests (Peh et al. 2006, Danielsen et al. 2009, Foster et al. 2011). Almost all organisms studied so far have lower species richness in oil palm plantations than in forests (Danielsen et al. 2009, Foster et al. 2011). This includes amphibians, wood-inhabiting fungi (Sheil et al. 2009), birds (Aratrakorn et al. 2006, Azhar et al. 2011, Jambari et al. 2012), plants (Gillison and Liswanti 1999, Foster et al. 2011), dung beetles, isopods, lizards (Foster et al. 2011), ants (Fayle et al. 2010), and mammals (Foster et al. 2011). Forest species, in particular, are missing. Fitzherbert et al. (2008) found that only 15% of primary forest species also occur in oil palm plantations when averaging across all taxa, while Danielsen et al. (2009) found that only 23% of vertebrates and 31% of invertebrates overlapped between forest and oil palm plantations. Among these, many species occur at lower abundances in oil palm plantations, this includes primates, small mammals, mosquitoes, birds, beetles, ants, and moths (Foster et al. 2011).

Some species are missing from oil palm plantations because they are intentionally killed. Trees are prevented from establishing in oil palm plantations and many animals are hunted. In particular, orangutans and elephants may be killed to prevent them from feeding on oil palms (Brown and Jacobson 2005) and tigers are killed if they are thought to be a threat to plantation workers (Brown and Jacobson 2005). In general, hunting pressure is higher in oil palm plantations than undisturbed forests because they are more accessible and closer to more people (Meijaard et al. 2005).

However, many species are missing from oil palm plantations because plantations do not provide them with suitable habitat. Oil palm plantations have a simpler structure than forests - their canopy is much lower, the upper canopy is dominated by only one species, and other growth forms of plants such as lianas are completely absent or reduced (Danielsen et al. 2009, Foster et al. 2011). Furthermore, conditions in an oil palm plantation are hotter, drier, and more light-transmissive than in a forest understory (Hardwick et al. 2015), instead being similar to the exposed conditions in the upper forest canopy. As a result, oil palm plantations are lacking the specific environmental conditions required by many forest species. Furthermore, oil palm plantations contain more weedy and exotic species than forests, and are exposed to more agrochemicals, further reducing the chances of survival for many species (Foster et al. 2011).

Biodiversity in oil palm plantations is expected to depend on plantation age (Luskin and Potts 2011) and management (Teuscher et al. 2015). It should increase with plantation age, as the canopy closes and structural complexity increases (Luskin and Potts 2011). In addition, there is some evidence that biodiversity is higher in smallholder than in large-estate plantations, at least for birds (Azhar et al. 2011, Jambari et al. 2012). Within smallholder plantations, Teuscher et al. (2015) have shown that the density of native trees has a positive effect on bird diversity and abundance.

Biodiversity loss in surrounding forests

The establishment of oil palm plantations also has negative effects on the habitat functions and biodiversity of surrounding contiguous forests and forest fragments (e.g., Edwards et al. 2010). First, plantation development usually increases access to forest areas, leading to increased hunting pressure and an increased likelihood of forest degradation and loss (Meijaard et al. 2005, Sheil et al. 2009). Second, plantation establishment often results in forest fragmentation, leading to edge effects, spillover effects, reduced species movement, greater population isolation, and greater risks of local and global extinction (Campbell-Smith et al. 2011, Fujinuma and Harrison 2012).

Mitigation

The habitat functions of oil palm plantations can be improved by changing management practices in planted areas and by maximizing the area of unplanted areas of native vegetation. In planted areas, management for biodiversity hinges on increasing the diversity of vegetation - through increasing the height, coverage, and diversity of ground cover plants and/or planting tree species (Koh 2008b, Koh et al. 2009). Unplanted areas can also act as a buffer zone to reduce impacts on adjoining forest areas (ECD 2002).

Research gaps
Research on biodiversity in oil palm plantations has so far focused largely on taxonomic *α*-diversity - the number of species occurring in a local area (but see e.g., Edwards et al. 2013). Studies on *β*- and *γ*-diversity (variation in species composition between localities, and regional diversity, respectively) are lacking (Fayle et al. 2013) and could reveal patterns of landscape and regional change. Additional studies on functional and phylogenetic diversity are also warranted, as these quantify different aspects of biodiveristy. Further, the role of adding habitat patches as refuges to increase functional biodiversity has not yet been quantified. Similarly, the influence of adjacent habitat type (jungle rubber, shrubland, rubber plantations or secondary forest) on community composition and ecological functioning inside oil palm plantations has been neglected so far.

(3) Production functions

(a) Food & raw materials

This function refers to the ability of an ecosystem to produce food and raw materials for human use. As oil palm plantations are managed specifically for palm oil production, this function is increased in oil palm plantations compared to forests. However, forests produce a wider variety of foods and raw materials.

Foods and materials from oil palm
Oil palm outperforms other oil crops such as rapeseed and soy by 3 to 8 times in production per hectare (Sheil et al. 2009). Oil palm plantations produce on average between 3 and 6 Mg of oil per hectare per year, and improved varieties and management could result in yields over 10 Mg per hectare per year (Fairhurst and Mutert 1999, Wahid et al. 2005, Zimmer 2010, Comte et al. 2012). Palm oil is produced from the fruit of the oil palm. After fruit bunches are harvested, they are processed in a local mill within 48 hours to prevent fruit deterioration (Vermeulen and Goad 2006). First, the stalks are separated from the fruits, leaving empty fruit bunches (EFB) as a byproduct. The fruits are then pressed, producing a press liquor that is separated into crude palm oil (CPO) and palm oil mill effluent (POME), a waste product that consists of an acidic mix of crushed shells, water, and fat residues. The CPO is refined and separated into solid and liquid fractions (Sheil et al. 2009). The press cake left over from pressing contains fibers, shells, and kernels (the seeds of the palm fruit); the kernels are ground, heated, and treated with a solvent to extract palm kernel oil (PKO; Poku 2002). Most CPO is used in food, while most PKO is used to produce detergents, cosmetics, plastics, and chemicals (Wahid et al. 2005).

Palm oil is the main output of palm oil plantations, but oil palm plantations also produce a variety of other goods. Palm kernel meal and POME can be used for animal feed, and livestock can be grazed in oil palm plantations (Corley and Tinker 2003, pp. 268–269). Intercropped plantations can also produce a range of other food crops (Corley and Tinker 2003, pp. 265–268). In Africa, oil palm sap is extracted, fermented, and distilled into palm wine (Corley and Tinker 2003). Oil palm trunks can be made into furniture (e.g., Suhaily et al. 2012), and other waste products (EFB, leaves, fruit shells, and fibers) can be used to make a variety of products (e.g., paper, activated carbon, and fish food, Ahmad et al. 2007, Bahurmiz and Ng 2007, Wanrosli et al. 2007). Finally, oil palm products can be used as fuels (e.g., Harsono et al. 2012),and in addition, POME can be fermented to produce methane/biogas (Yacob et al. 2006), and oil palm waste products can be burned directly (Yusoff 2006).

Loss of forest foods and materials
Forests support many species that oil palm plantations do not, including many species used for food and other raw materials. These forest resources are especially important during times of crop failure (Sheil et al. 2006). In addition, forests in many regions are used for the cultivation of rattan and rubber, and for swidden/slash and burn agriculture (Sheil et al. 2006, van Noordwijk et al. 2008). The loss of these forest products and forest agriculture due to conversion to oil palm has negatively impacted many forest-dependent communities (Belcher et al. 2004, Sheil et al. 2006).

Mitigation
Some forest plants could potentially be cultivated in oil palm plantations to prevent the loss of some forest products.

Research gaps
This is a well-researched ecosystem function regarding oil palm plantations and our database only reflects a fraction of the total research on this topic because the scope of our study only included local production (i.e., direct products from the plantation and not downstream production) reported from studies in the scientific literature). A summary of active research topics is given by Corley and Tinker (2003, p. 479). Additionally, the full range of forest species that can be used for food and raw materials is doubtless unknown and additional ethnological surveys of forest-dependent communities would be useful.

(b) Genetic resources

This function refers to the gene pool of organisms in an ecosystem which might be used to improve cultivated species (de Groot et al. 2002). Considerable research has gone into measuring genetic variability of oil palms (e.g., Cochard et al. 2009). Most oil palm monocultures are derived from genetically limited sources, consequently oil palm monocultures themselves show very limited genetic variation (Thomas et al. 1969, Corley and Tinker 2003). With clonal propagation of oil palms, genetic variation in oil palm plantations is expected to decrease even further due to the planting of high-yield clones (Corley and Tinker 2003). As oil palm plantations have reduced species' richness and species' abundances for most species relative to forests (see section *III. 2a*), the potential for maintaining many genetic resources in other organisms is also greatly reduced.

Mitigation

Much of this loss cannot be mitigated. However, on-going breeding programs can make conservation of genetic diversity a priority (Corley and Tinker 2003). Considerable natural genetic variation exists, and several organizations maintain oil palms of a variety of genetic origins (e.g., the Malaysian Palm Oil Board, Hayati et al. 2004). Breeding can be carried out selectively to maintain genetic diversity while still preserving local co-adapted traits (Corley and Tinker 2003). In addition, genetic modification has the potential to increase yield and resistance to disease and stress (Corley and Tinker 2003). Mitigation measures for biodiversity loss (see section *III. 2a. Refugium & nursery functions: mitigation*) will also help to maintain genetic resources.

Research gaps

Research gaps include quantifying the non-oil palm genetic resources lost with conversion from forest and researching the necessary steps to prevent their irreversible loss. For oil palm, research on the appropriate balance between selection for uniformly high yielding strains and the maintenance of genetic diversity necessary to convey disease and disturbance resistance is needed.

(c) Medicinal resources

This function refers to medicinal resources derived from the organisms in an ecosystem. Most of the studies found were regarding nutritional benefits of palm oil and oil palm leaf extract. However, forests contain a greater diversity of species than do oil palm plantations (see *section III. 2a.*), and many of these species have been found to be medicinally useful (e.g., over 2000 Southeast Asian forest species are used in women's healthcare, de Boer and Cotingting 2014), while others remain to be tested. Consequently, the expansion of oil palm plantations represents a loss in this function at local, regional, and global scales, compared to forest. Measures to mitigate this loss will be difficult as the medicinal properties of many species remains unknown (especially for species unknown to science).

Medicinal benefits of oil palm

Documented uses of palm oil include treating prostate diseases, use as a component in skin lotion, and as a carrier for medicinal extracts of other plants (Arsic et al. 2010, 2012, Emmanuel 2010). Historically, palm oil has been used for soap production (Henderson and Osborne 2000). Traditional use of leaf extract has led to its study for wound-healing and antimicrobial properties (Chong et al. 2008, Sasidharan et al. 2010, 2012), and the role of its antioxidants in treating disease (e.g., diabetes, Rajavel et al. 2012). Anecdotally, a variety of uses have been ascribed to oil palm, including all parts of the plant (Opute 1975, Chong et al. 2008).

Research gaps

Both the medicinal uses of oil palm products and the discovery of new medicinally useful species remain active fields of research. Research cataloguing the biodiversity of Southeast Asian forests and its medicinal properties may allow species of medicinal importance to be conserved and their medicinal benefits retained. Such studies should be guided by traditional ecological knowledge and detailed ethnobotanical research. Studies of medicinal uses of oil palm products would also benefit from ethnobotanical studies, and medicinal claims should be backed up by clinical, double-blind studies published in reliable medical journals.

(d) Ornamental resources

This function refers to organisms in an ecosystem which are used ornamentally, for instance as garden plants, collector's items, or materials for clothing or crafts (de Groot et al. 2002). Ornamental resources have been found to decrease in cultivated land relative to forests (Sheil and Liswanti 2006). Therefore, we hypothesize that this ecosystem function would be reduced in oil palm plantations relative to forests, but as we found only two studies, more research on this topic is necessary. We see no way to mitigate this loss, apart from the cultivation of ornamentally useful forest species within oil palm plantations.

(4) Information functions

(a) Aesthetic information, *Recreation*, *Cultural & artistic information/inspiration*, *Spiritual & historic information*, *and Science & education*

Information functions are the intangible benefits that people get from an ecosystem, or in other words, the intangible values that an ecosystem holds for people. De Groot et al. (2002) classify information functions into aesthetic information, recreation and tourism, cultural and artistic inspiration, spiritual and historic information, and scientific and educational information. We discuss the information functions all together, as we found only 30 papers relevant to information functions in oil palm plantations. In part, this is due to an emphasis of sociological research on the socioeconomic benefits of oil palms instead of on intangible information functions. In addition, the terminology of cultural services and information functions is not used within all articles, consequently some topical articles may have been missed. In general, the conversion of forest to oil palm cultivation leads to a large loss in information functions.

Information functions associated with oil palm and palm oil
In its native range, locations where oil palms are growing are considered sacred places (Gruca et al. 2014). Several parts of the palm, including palm oil, are integrated into local traditions and customs (e.g., local food cultures, Atinmo and Bakre 2003, Gruca et al. 2014, and in other ritual ceremonies and traditional medicines, Gruca et al. 2014). Outside its native range, oil palms may also be incorporated into local culture and traditions. In Bahia, Brazil, agro-ecological cultivation of oil palm in polyculture has resulted in a local cultural landscape (Watkins 2015). In Jambi province, Sumatra, Indonesia, smallholder farmers were found to perceive small oil palm plantations as clean and beautiful, in contrast to formerly present agroforests (Therville et al. 2011). In contrast, large oil palm monocultures are typically associated with few information functions (Watkins 2015).

Turning towards science and education, local palm oil industries achieve learning effects through international cooperation, technology transfer, and internal learning (Manik et al. 2013, Hansen and Ockwell 2014). In some instances, oil palm expansion results in improved education for plantation workers and their families (Sheil et al. 2009, German et al. 2011). Further, oil palm plantations and agriculture have been the subject of extensive agronomic, economic, and environmental science research. Indirectly, however, and as a consequence of some negative impacts of oil palm plantations, there have been campaigns to raise public-awareness for conservation issues (e.g., Australia's "Don't Palm Us Off" campaign, Pearson et al. 2014).

Information functions lost with forest conversion to oil palm

Unlike oil palm plantations, forests are valued highly for health, cultural and spiritual purposes (Pfund et al. 2011, Meijaard et al. 2013), recreation (Sheil and Liswanti 2006, Sheil et al. 2006, Ratnasingam et al. 2014), and tourism (Bennett and Reynolds 1993, Broadbent et al. 2012, Burke and Resosudarmo 2012). In addition, pollution generated by palm oil plantations results in reduced aesthetic beauty and recreational potential (Koh et al. 1991). The difference in information functions between forest and oil palm is particularly large for those people who traditionally depend on forests for their livelihoods (Manik et al. 2013). In contrast, Feintrenie et al. (2010) found that people tend to weight financial interests over cultural or sentimental attachment. Belcher et al. (2004) integrated financial and cultural aspects into an analysis of preferences for different land use types (agroforest, monoculture) and crops (rattan, rubber, oil palm) and had similar findings to Feintrenie et al. (2010). We would also guess that forests provide more and a greater variety of subjects for research and education than oil palm plantations.

Mitigation

Some information functions, such as spiritual and historic information, are linked to certain species or places. Consequently, prioritizing the conservation of those species and places could maintain some information functions. However, oil palm plantations and forests are qualitatively different environments and we do not see any way to mitigate the loss of many information functions resulting from forest conversion to oil palm.

Research gaps

Not much research on information functions has been conducted. Consequently, information functions are proportionally under-represented among ecosystem functions (Fig. 4b). Instead, research has focused on socio-economic benefits and human well-being following land use change, instead of on information functions (following de Groot et al. 2002) or cultural ecosystem services (see, e.g., Millennium Ecosystem Assessment 2005).

IV. DISCUSSION

Impacts of oil palm plantations

In this review we have shown that, with few exceptions, oil palm plantations have reduced ecosystem functioning compared to forests. The greatest impacts are on gas regulation, water regulation and supply, habitat functions, and information functions. Food production is the only function that is increased in oil palm plantations; with proper management, it may be possible to maintain some other functions (water regulation, disturbance regulation, soil retention, nutrient regulation, and waste treatment) at forest levels.

We have also shown that evaluating ecosystem functions in oil palm plantations is not straightforward. First, many functions are interrelated - for instance, poorer water regulation in oil palm plantations also leads to increased risks of disturbance and greater losses of soil and nutrients. Second, ecosystem functioning changes throughout the life cycle of an oil palm plantation, with greatest losses in functioning during plantation establishment, when land is cleared, and a gradual restoration of many functions as plantations mature. Finally, ecosystem functioning in oil palm plantations depends heavily on plantation management practices, which vary greatly.

Options for mitigation

The negative impacts of oil palm plantations can be reduced through improved plantation management and stopping the conversion of forest to oil palm (Yusoff and Hansen 2007, Comte et al. 2012, Schrier-Uijl et al. 2013). This includes indirect conversion where oil palm replaces other cultivated land, and the other cultivated land then replaces the forest (i.e., the cascade effect, Lambin and Meyfroidt 2011). In this review we have described a wide range of plantation management practices that can improve ecosystem functions. Many of these management practices contribute to improving multiple ecosystem functions at once (e.g., the establishment of a diverse ground cover). We also point out that some of these management practices, such as clearing land without burning, may be required by law, but are not consistently enforced (Sheil et al. 2009). Enforcing these existing regulations would be a good step forward. Finally, impacts of oil palm agriculture and losses in ecosystem functions could be greatly reduced by stopping the conversion of forest (especially peat forest) to oil palm, and establishing new oil palm plantations only on degraded or agricultural land instead (Härdter et al. 1997, Yusoff and Hansen 2007, Reijnders and Huijbregts 2008). This is already agricultural policy in Malaysia (Tan et al. 2009), although debate continues over what land is defined as acceptable for oil palm (Koh and Wilcove 2008). The ecosystem function losses associated with loss of some forested areas cannot be mitigated (e.g., forested areas critical to the persistence of endemic forest-specialist species). In order to maintain certain global ecosystem functions (e.g., medicinal resources, habitat and nursery functions), these areas would need to remain uncleared, and cleared areas would need to be returned to forest cover.

Considerations of scale: spatial, temporal, and plantation

Oil palm plantations affect ecosystem functioning at different spatial scales. At the global scale, food and raw material production functions are increased with a corresponding loss of climate regulation, habitat functions, and genetic, medicinal and ornamental resources. At the regional scale (countries/islands), air quality, water regulation and disturbance prevention functions are decreased. At the local scale (plantation and immediate surroundings), air quality, water regulation, disturbance prevention, and soil retention are decreased. At the local scale, nutrient regulation is changed, potentially also at the regional scale through fertilizer runoff. Aside from additional waste production, the effects on local waste treatment ecosystem functioning are unclear. The local and regional effects on pollination and biocontrol are also unclear. Educational and scientific information functions are lost at all scales, due to a loss of species diversity associated with the loss of forest (e.g., Foster et al. 2011).

Ecosystem functioning shows strong temporal patterns as well. Most decreases in ecosystem functioning occur with the loss of forest or with draining of peat (i.e. GHG emissions, air quality reduction, water regulation changes, disturbance prevention, soil retention, and loss of information functions). Some recovery of ecosystem function occurs with the establishment of the plantations (e.g., carbon fixation by oil palms, stabilization of soil with establishment of ground cover). Production functions are also temporal, starting out at zero at establishment, reaching a peak at intermediate plantation age, and then declining as the palms reach heights that are difficult to harvest (Sheil et al. 2009). Many of the temporal effects on ecosystem functioning are mediated by plantation management. For example, nutrient regulation depends strongly on fertilizer application and mulching approach (Comte et al. 2012).

A third scale important to oil palm effects on ecosystem functioning, is the scale at which the planting is carried out. Economies and diseconomies of scale affect ecosystem functions on oil palm plantations (Klasen et al. *unpubl. data*). However, for many ecosystem functions, the difference in effect on ecosystem functions, if any, between small and large plantations is unknown (e.g., water regulation, soil loss, pollination, biological control).

Major research gaps

Apart from the specific research gaps we identified for each ecosystem function, there is a general need for more data (Comte et al. 2012). Most of the studies we reviewed are based on a small number of observations in a small number of oil palm plantations and thus give only a limited, coarse-scale picture of what is going on. In particular, it would be useful to have more data from comparative studies to pick apart the influences of plantation age, local environmental conditions, and plantation management on ecosystem functioning. More studies explicitly considering plantation management and plantation type would especially be useful, as there are qualitative differences between smallholder and large-scale plantations (Azhar et al. 2011, Harsono et al. 2012, Jambari et al. 2012), management practices vary greatly among plantations (Vermeulen and Goad 2006, Comte et al. 2012), and this factor has largely been neglected. Finally, it would be optimal if these studies were carried out by local scientists, who are likely to have the most complete and up-to-date knowledge (Sheil et al. 2009).

V. CONCLUSIONS

1. This paper discussed comprehensive ecosystem functions of oil palm based on the classification made by de Groot (2002), followed by identification of research gaps and possible mitigation management practices for each ecosystem function.
2. Ecosystem functions in the regulation, habitat, and information categories tend to decrease in oil palm ecosystems under a business as usual (BAU) condition when compared to forest as a reference land use. The decreasing trends are varied depending on plant ages, soil types, and spatial scale. The degree of degradation is more intense when oil palm is grown in peatlands and on sandy soils. On the other hand, the production ecosystem function of oil palm is higher compared to that of forest.
3. This review included some research results from short-term studies with weak measurement and statistical methods. In this respect, this paper revealed that there is a great need for larger studies, over longer time periods, with more measurements, comparing a wider range of environments and management practices. This paper also described a wide range of plantation management practices that can improve ecosystem functions compared to those in the BAU condition
4. By knowing how oil palm affects the degree and the direction of changes to ecosystem functions for each category, a trade-off can be best sought to reduce degradation of ecosystem functions and to increase socio-economic functioning.

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