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A review of the ecosystem functions in oil palm plantations, using forests as a reference system

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ABSTRACT

Oil palm plantations have expanded rapidly in recent decades. This large-scale land-use change has had great ecological, economic, and social impacts on both the areas converted to oil palm and their surroundings. However, research on the impacts of oil palm cultivation is scattered and patchy, and no clear overview exists. We address this gap through a systematic and comprehensive literature review of all ecosystem functions in oil palm plantations, including several (genetic, medicinal and ornamental resources, information functions) not included in previous systematic reviews. We compare ecosystem functions in oil palm plantations to those in forests, as the conversion of forest to oil palm is prevalent in the tropics. We find that oil palm plantations generally have reduced ecosystem functioning compared to forests: 11 out of 14 ecosystem functions show a net decrease in level of function. Some functions show decreases with potentially irreversible global impacts (e.g. reductions in gas and climate regulation, habitat and nursery functions, genetic resources, medicinal resources, and information functions). The most serious impacts occur when forest is cleared to establish new plantations, and immediately afterwards, especially on peat soils. To variable degrees, specific plantation management measures can prevent or reduce losses of some ecosystem functions (e.g. avoid illegal land clearing *via* fire, avoid draining of peat, use of integrated pest management, use of cover crops, mulch, and compost) and we highlight synergistic mitigation measures that can improve multiple ecosystem functions simultaneously. The only

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ecosystem function which increases 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 socio-cultural information functions. Further, there is a need for more empirical data on the importance of spatial and temporal scales, such as differences among plantations in different environments, of different sizes, and of different ages, as our review has identified examples where ecosystem functions vary spatially and temporally. Finally, more research is needed on developing management practices that can offset 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 cultivation.

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

CONTENTS

I. INTRODUCTION

(1) Scope and overview

Over the past few decades, oil palm plantations have expanded dramatically, especially in Southeast Asia (e.g. Koh, 2011; see online Appendix S1). As the production of palm oil is highly cost- and area-effective compared to other oil crops (e.g. Zimmer, 2010), this trend is projected to continue in Southeast Asia and other tropical regions (Fitzherbert *et al.,* 2008). During the past few years, the scientific community has given increasing attention to oil palm expansion and its consequences for ecosystems and people. However, research on the environmental impacts of oil palm cultivation has been fragmented by discipline. While natural scientists have mostly focused on the contributions of oil palm expansion to the loss of rainforest, biodiversity, and soil carbon as well as greenhouse gas emissions (e.g. Fargione *et al.,* 2008; Barnes *et al.,* 2014; van Straaten *et al.,* 2015), economists have discussed costs and benefits associated with development (Corley, 2009). Social scientists have drawn attention to large-scale oil palm cultivation in relation to land grabbing (Hall, 2011; Borras & Franco, 2012) and land-use conflicts between local communities and oil palm companies (Afiff & Lowe, 2007; Potter, 2009; Colchester *et al.,* 2011; Steinebach, 2013). The impact of agro-industrial oil palm cultivation on local social structures, e.g. plantation workers who interact or conflict with indigenous communities (Dove, 2005; van Klinken, 2008), has been investigated as well as how gender relationships are influenced by new labour requirements (Li, 2014). The interaction of large-scale oil palm cultivation and social transformation still requires further scientific investigation and is beyond the scope of our review.

Here we present an interdisciplinary, comprehensive overview of the environmental consequences of oil palm expansion. We first summarize the process of oil palm cultivation (Section I.2), and its direct effects on biodiversity (Section I.3). We then use ecosystem functions as a unifying framework to synthesize research results from natural sciences, economics, and social sciences. 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, Wilson & Boumans, 2002). While ecosystem functions are related to ecosystem services, an ecosystem function is the ecosystem's capacity to provide a given service, regardless of whether the service is actually utilized (e.g. an ecosystem may be able to treat more organic waste than is present). Ecosystem functions are grouped into four main categories: regulation, habitat, production, and information. Regulation functions maintain biogeochemical cycles, e.g. carbon sequestration, and water and nutrient cycling. Habitat functions support biological 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).

We reviewed these ecosystem functions systematically (Section II) to assess the change in ecosystem function in oil palm plantations relative to forest (the dominant ecosystem replaced by oil palm; Koh & Wilcove, 2008), summarize mitigation actions that can be taken to maintain ecosystem functions, assess which ecosystem functions are understudied, and highlight important research gaps for each ecosystem function (Sections III.1–14 and IV.2–4). Where data are available, we also consider the spatial, temporal, and management (smallholder *versus* large-scale plantations) scales at which changes in ecosystem functions occur (Section IV.4; Rodríguez *et al.,* 2006).

(2) Oil palm cultivation and oil production

Elaeis guineensis Jacq., the species most broadly used for palm oil production, is native to tropical Africa, with its native range extending from Guinea to Angola (Corley & Tinker, 2003). Easy establishment, low costs, and high output make oil palm a highly profitable tropical cash crop and economically the most efficient ($Mg\,ha^{-1}$) oil crop in the world (Wahid, Abdullah & Henson, 2005). Oil palms are now grown throughout the humid tropical lowlands (18.1 million ha in 43 countries), with Indonesia (7.1 million ha) and Malaysia (4.6 million ha) together accounting for about 85% of global crude palm oil production (see online Appendix S1, data to 2013; FAO, 2015). Oil palms grow on a range of soil types, including soils where few other crops grow successfully (Corley & Tinker, 2003). The costs of palm oil production are low because oil palms require relatively low fertilizer inputs per Mg of oil produced (but still may require large absolute amounts of fertilizer). Also, they 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 often requires heavy machinery in the case of large-scale plantations, which can lead to soil compaction (Lal, 1996) among other soil physical degradations. Clearing through slashing and burning removes aboveground biomass, understorey vegetation, and ground litter and thus results in 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 1990s in Malaysia and Indonesia), it remains the common practice (Murdiyarso *et al.,* 2004; DeFries *et al.,* 2008). If a plantation is being established in peat lands, the next step is drainage, as oil palms cannot grow on waterlogged peat soils. This results in even higher carbon losses than from plantation establishment alone (Fargione *et al.,* 2008). Next, roads/tracks are built, along with drainage ditches and, in some cases, terraces. Oil palm seedlings are then planted at densities of about 110–150 palms per hectare (Sheil *et al.,* 2009). After 2–3 years, the palms mature and fruits can be harvested. Oil palm production peaks at 9–18 years (USDA FAS, 2012), but palms are left on the field for up to 25–30 years until they become too tall for fruit harvest (Basiron, 2007; Sheil *et al.,* 2009). At this point, the palms are usually cut down and new seedlings are planted (see Fig. 1 for oil palm plantations at different stages of growth). After oil palm fruit bunches are harvested, they need to be processed in a local mill within 48 h to prevent fruit deterioration (Vermeulen & Goad, 2006). First, the stalks are separated from the fruits, leaving empty fruit bunches as a by-product. The fruits are then pressed, producing a press liquor that is separated into crude palm oil and palm oil mill effluent (POME). The crude palm oil is refined and separated into solid and liquid fractions (Sheil *et al.,* 2009). The press cake left over from pressing contains fibres, shells, and kernels (the seeds of the palm fruit); the kernels are ground, heated, and treated with a solvent to extract palm kernel oil (Poku, 2002). Most crude palm oil is used in food, while most palm kernel oil is used to produce detergents, cosmetics, plastics, and chemicals (Wahid *et al.,* 2005). Empty fruit bunches and POME, a waste product that consists of an acidic mix of crushed shells, water, and fat residues, are the main organic wastes produced.

Oil palm plantations usually occur either as large-scale plantations (3000–20000 ha; Sheil *et al.,* 2009) or as family-based smallholder plantations (defined as <50 ha, most around 2 ha; Vermeulen & Goad, 2006). Large-scale plantations usually include a processing mill, and are mainly owned by private companies, with a minority being state-owned (Central Bureau of Statistics Indonesia, 2014, p. *xx*). Smallholder plantations make up about 40% of the land under oil palm cultivation in Indonesia and 13% in Malaysia (Malaysian Palm Oil Board 2012, cited by Azhar *et al.,* 2014; Central Bureau of Statistics Indonesia, 2014).

Smallholders either work independently or as supported smallholders. Independent smallholders are self-financed, manage their own farms, and may deal directly with the local mill operators of their choice or even process their own palm oil using their own or community-owned manual palm oil presses (Zoological Society London, 2015). Supported smallholders are linked to large-scale plantations and receive support on material inputs, training, and plantation preparation (Sheil *et al.,* 2009). In return for this assistance, supported smallholders commit to selling their crops to a large-scale 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 scheme of the 1990s (Fearnside, 1997; Budidarsono, Susanti & Zoomers, 2013) utilized in the villages of Jambi province (Indonesia), the large-scale plantations allocated 30% of their land for their core oil palm plantation while 70% was available for use by participating smallholders. In the last decade, the partnership model has arisen, where the core estate retains up to 80% of its land and makes only the remaining share of the land available to smallholders (McCarthy, 2010).

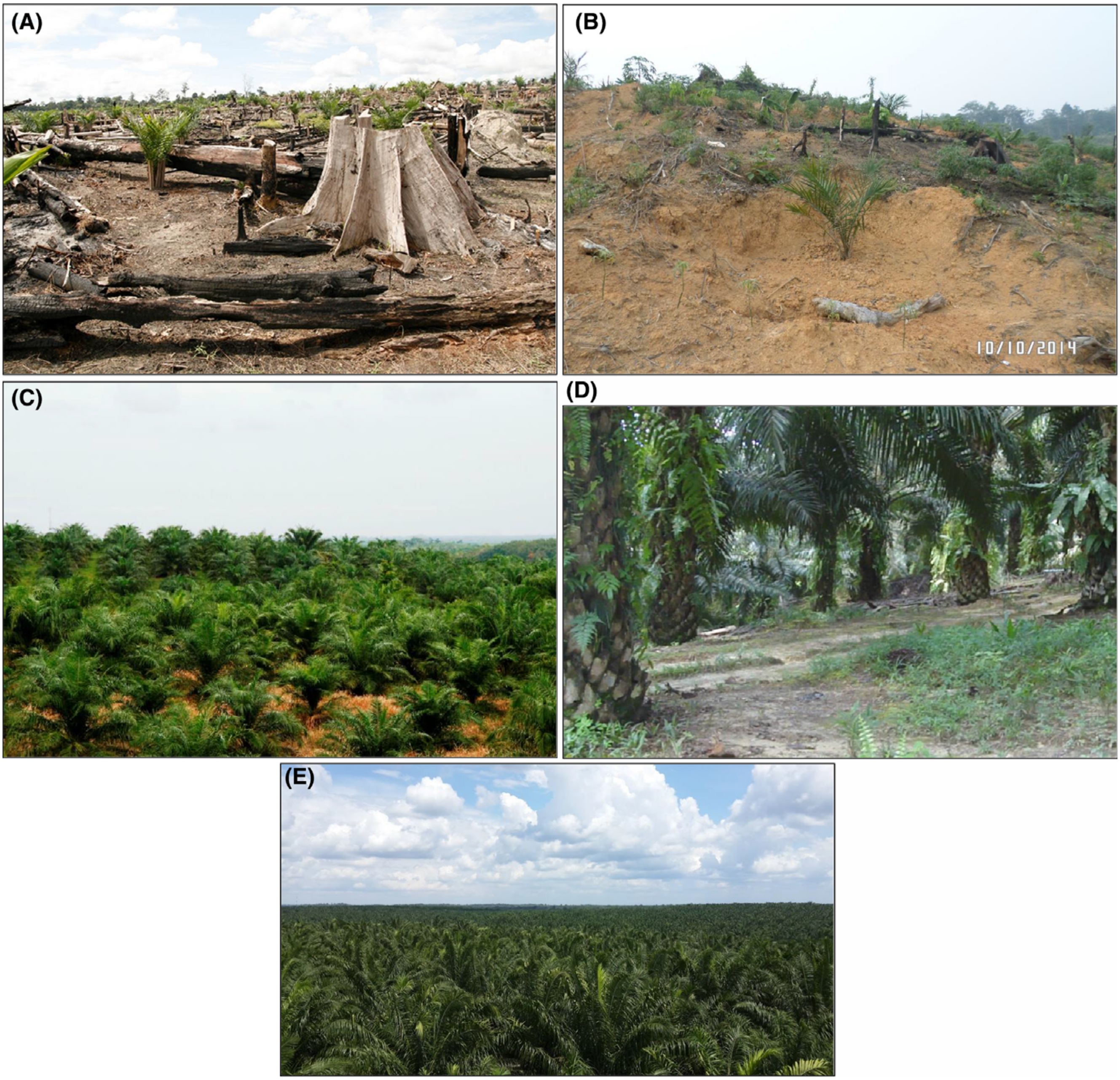

Fig. 1. Examples of oil palm plantations (Jambi, Indonesia) in different stages of establishment: (A, B) initial establishment, (C) a young plantation, and (D, E) a mature oil palm plantation. Photo credits: A, C, D, Oliver van Straaten, 2010; B, Suria Tarigan, 2014; E, Ana Meijide, 2015.

(3) Biodiversity

Biodiversity is a multifaceted concept that includes the diversity of life on different levels of organization from genes, to species, to entire ecosystems. Biodiversity as such is not an ecosystem function but is important to many ecosystem functions. Conversion of forest to oil palm clearly represents a major threat to biodiversity (see reviews by Fitzherbert *et al.*, 2008; Danielsen *et al.*, 2009; Yule, 2010; Foster *et al.*, 2011; Savilaakso *et al.*, 2014; Drescher *et al.*, 2016). Most studies on oil palm have investigated species richness in small sampling plots. Almost all organisms studied so far have lower species richness in oil palm plantations than in forests, including wood-inhabiting fungi, plants, litter invertebrates, dung beetles, ants, amphibians, lizards, birds, and mammals (Gillison & Liswanti, 1999; Aratrakorn, Thunhikorn & Donald, 2006; Maddox *et al.*, 2007; Danielsen *et al.*, 2009; Fayle *et al.*, 2010; Azhar *et al.*, 2011; Foster *et al.*, 2011; Gillespie *et al.*, 2012; Hattori, Yamashita & Lee, 2012; Jambari *et al.*, 2012; Barnett *et al.*, 2013; Faruk *et al.*, 2013; Barnes *et al.*, 2014; Drescher *et al.*, 2016). Not only is species richness lower, the species that are present are more likely to be common, generalist species (Yule, 2010) while forest species tend to be absent. 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 (also *cf*. Yaap *et al.,* 2010). Functional diversity of dung beetles and birds has also been found to be reduced in oil palm plantations (Edwards *et al.,* 2013, 2014*a*), although more studies on functional diversity are needed (but see Senior *et al.,* 2013; Mumme *et al.,* 2015). Abundances are lower in oil palm plantations for many taxa, including ants, beetles, moths, mosquitoes, birds, small mammals, and primates (Foster *et al.,* 2011), although some taxa, while still less diverse, may have higher abundances (i.e. dung beetles, isopods, lizards, and bats; Foster *et al.,* 2011; and some species of birds, ants, and beetles, Senior *et al.,* 2013). The loss of biodiversity in oil palm plantations is due to loss of habitat (see Section III.9), altered habitat characteristics (e.g. vegetation structure and microclimate; Drescher *et al.,* 2016), increased access to species of food or commercial interest (e.g. access for hunting; Meijaard *et al.,* 2005), and direct removal of species considered to be pests (including orangutans, elephants, and tigers; Brown & Jacobson, 2005).

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 1, Fig. 2). To improve accuracy, some functions were updated based on de Groot *et al.* (2010). We based our review on a structured literature search, but did not conduct a formal meta-analysis, as too few studies reported suitable effect sizes for comparison. For each of these functions we developed a list of search terms (see online Appendix S2). We then used the search terms in combination with 'oil palm', 'palm oil', or 'elaeis guineensis' to search *Web of Knowledge* for publications between 1970 and mid-February 2015. Our searches returned many off-topic articles, as evidenced by their titles and abstracts, and these were removed from further consideration. The remaining studies, plus additional relevant articles and reports that were found during the preparation of this review, were organized as a JabRef literature database (see online Appendix S3; JabRef Development Team, 2015). Each ecosystem function was assigned to two or more section authors, who used the literature database and their knowledge of the topic to write the narrative portion of this review. Where available, the section authors 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 findings that to our judgment are the most important and novel. The results from each narrative were then synthesized based on expert opinion to arrive at a net effect for each ecosystem function. We acknowledge that different experts could arrive at different conclusions, but present the rationale for each decision in online Appendix S4.

Table 1. Summary of the number of relevant studies found in the literature search. The categories Regulation, Habitat, Production, and Information functions are indicated by R, H, P, and I, respectively. Gas & climate regulation and Refugium & nursery functions were the most studied ecosystem functions, while Ornamental resources was the least studied. See online Appendix S3 for a complete list of references

Ecosystem function[a]	Studies
1. (R) Gas & climate regulation	204
2. (R) Water regulation & supply	89
3. (R) Moderation of extreme events	54
4. (R) Erosion prevention[b]	60
5. (R) Soil fertility[b]	103
6. (R) Waste treatment	38
7. (R) Pollination	36
8. (R) Biological control	109
9. (H) Refugium & nursery functions	217
10. (P) Food & raw materials	140
11. (P) Genetic resources	47
12. (P) Medicinal resources	80
13. (P) Ornamental resources	14
14. (I) Information functions	30
Total[c]	955

[a]The following ecosystem functions from de Groot *et al.* (2002) were combined: gas regulation and climate regulation; water regulation and water supply; nutrient regulation and soil formation; refugium function and nursery function; food and raw materials; and aesthetic information, recreation, cultural & artistic information, spiritual & historic information, and science and education. This resulted in 14 instead of 23 ecosystem functions.
[b]Soil retention was updated to erosion prevention and nutrient regulation was updated to soil fertility for increased clarity (de Groot *et al.,* 2010).
[c]Note that a study may be included in more than one category, hence the sum of the studies in the 14 functions exceeds the total number of studies.

We focus our review on ecosystem functions in monocultures. In their native range, oil palms are often grown in mixed-species agroforestry systems (Poku, 2002), which we expect to differ in ecosystem functioning. However, such farms make up only a tiny fraction of the world's oil palm production. We focus on ecosystem functions that arise within and immediately surrounding oil palm plantations rather than downstream effects of palm oil use or indirect effects of the oil palm industry. These indirect impacts have been treated elsewhere (e.g. Sheil *et al.,* 2009; Achten & Verchot, 2011).

We use forests as a reference point because they are the potential natural vegetation in most areas where oil palm plantations are established. We do not distinguish between primary and secondary forests because differences between them in ecosystem functions are expected to be small compared to the differences between either type of tropical forest and oil palm plantations (e.g. Edwards *et al.,*

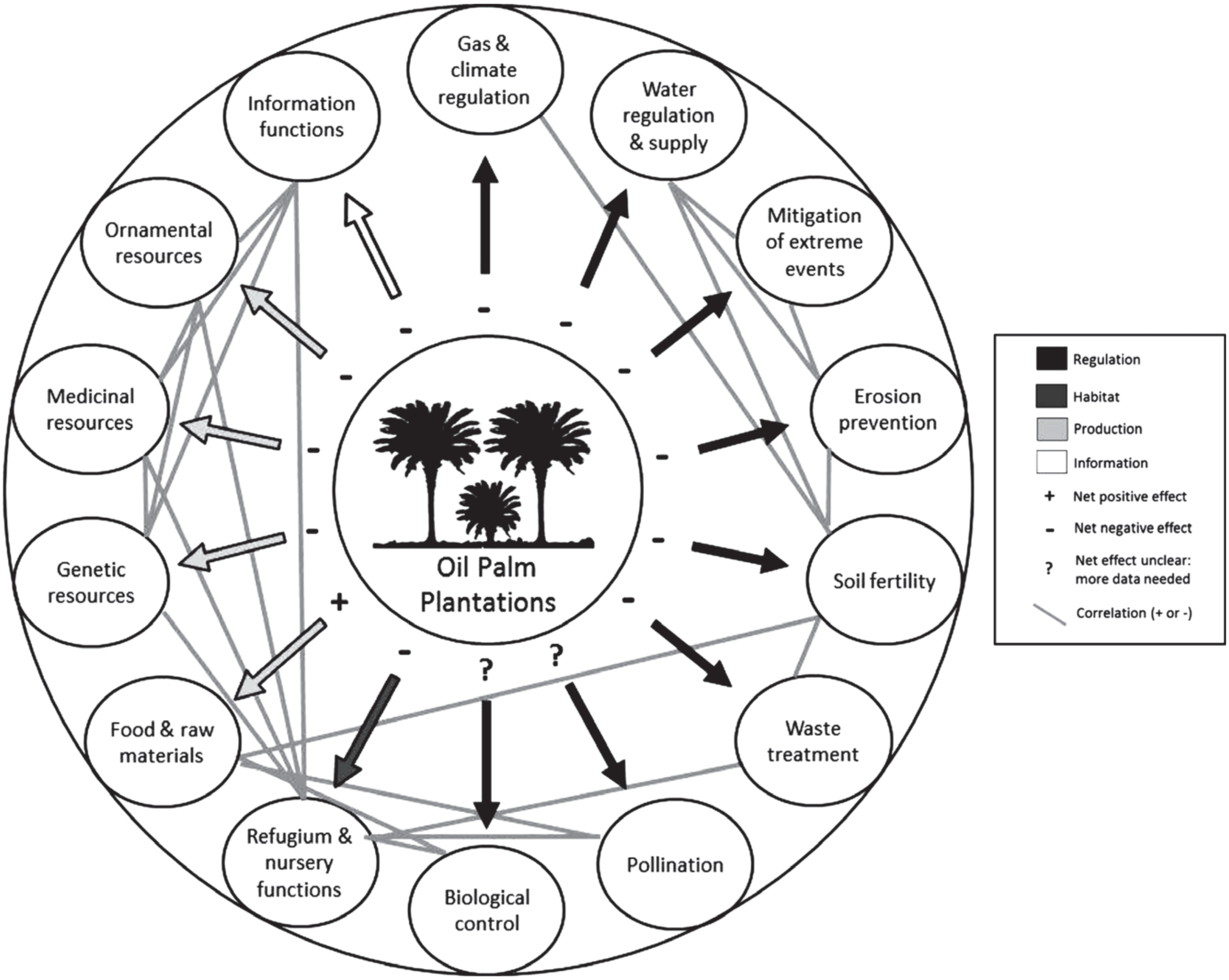

Fig. 2. Oil palm plantations have a predominantly negative net effect on ecosystem functions when compared to primary and secondary rainforest. Net effects do not imply that all effects on a given ecosystem function are positive or negative, but that the majority or most-dominant effects are in the given direction. See Table 2 for additional details. Estimates of net effect direction and correlation are qualitative and are based on the summary presented herein.

2011). 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 (e.g. Koh & Wilcove, 2008; Sheil *et al.,* 2009), and this comparison therefore provides a useful upper bound for possible changes in ecosystem function.

III. RESULTS

In total, we found 955 studies and reports dealing with ecosystem functions in oil palm plantations (Table 1, see online Appendix S3), with an increase in publication rate over time. 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 and Ornamental resources, Table 1). Overall, oil palm had a predominantly negative effect on 11 of the 14 ecosystem functions relative to native rainforest (Table 2, Fig. 2). However, for many ecosystem functions, oil palm had both positive and negative effects (Table 2).

(1) Gas & climate regulation

Gas and climate regulation refers to biotic and abiotic processes of terrestrial ecosystems influencing the atmosphere. It includes biogeochemical cycles associated with greenhouse gas (GHG) emission and air quality, as well as biophysical processes which regulate climate through

Table 2. Changes in ecosystem functions with conversion of forest to oil palm plantations (−, decrease; +, increase). The change in ecosystem function relative to intact forest is given for deforested land (e.g. Fig. 1A, B), young plantations (e.g. Fig. 1C), and mature plantations (e.g. Fig. 1D, E). Plantations on peat soils have additional negative effects on ecosystem function not captured in this table. ++ or − − indicates qualitatively larger effects (based on expert opinion); = indicates no detectable changes; ? indicates absent or insufficient data, thus highlighting important research gaps. In some cases where no studies have been conducted, existing research suggests an expected direction or outcome. These instances are indicated with the expected direction and a footnote (6) to clarify that the direction is hypothesized, but not confirmed

 Ecosystem sub−function[a]	 Deforested land	 Young plantation	 Mature plantation
(1) Soil carbon storage	− −	−	−
(1) Biomass carbon storage	− −	− −	−
(1) N_2O balance[b]	− −	− −	−/+/=
(1) CH_4 balance[c]	?	?	−
(1) Air quality	− −	?	−
(1) Volatile organic compound balance[b]	− −	?	−
(2) Water storage	− −	− −	−
(2) Water yields	++	+	?
(1, 2) Actual evapotranspiration	− −	?	=
(2) Infiltration rate	−	−[d]	−[d]
(2) Regularity of supply (baseflow)	−	−	?
(2) Regulation of peak flows	− −	−	?
(2, 4) Water quality: low sediment loads	− −	−	−[e]
(2, 6) Water quality: low pollution	−	−[e]	−[e]
(2, 3) Flood prevention	−/− −	−/− −[e]	−/− −[e]
(2, 3) Drought prevention	−	−[e]	−[e]
(3) Landslide prevention	− −[f]	− −[f]	−[f]
(3) Wildfire prevention	− −	−[e]	−[e]
(4) Erosion prevention	− −	−	−
(5) Organic nutrient retention	− −	− −[e]	−[e]
(5) Nutrient inputs	?	++[e]	++[e]
(6) Treatment of organic waste	−[f]	−[f]	−[f]
(6) Treatment of inorganic waste	?	?	+
(6) Decomposition rate	?	=[e]	=[e]
(6) Noise abatement	?	?	?
(7) Pollination: plantations	− −[f]	?	?
(7) Pollination: surrounding areas	−[f]	?	?
(8) Biological control: plantation	?[g]	−/+[e, g]	−/+[e, g]
(8) Biological control: surrounding area	?[g]	?[g]	?[g]
(9) Species richness: plantation	− −	− −	− −
(9) Species richness: surrounding area	− −	− −[e]	− −[e]
(9) Species' abundance: plantation	− −	− −/++[e]	− −/++[e]
(9) Species' abundance: surrounding area	?	?	?
(9) Dispersal functions	− −[f]	− −[f]	− −
(10) Food/raw materials: quantity	− −	?	++
(10) Food/raw materials: diversity	− −	− −[e]	− −[e]
(11) Genetic resources	− −	− −[e, f]	− −[e, f]
(12) Medicinal resources	− −	− −[e, f]	− −[e, f]
(13) Ornamental resources	− −	−[e]	−[e]
(14) Aesthetic appeal	− −	− −/+[e, f]	− −/+[e, f]
(14) Cultural and artistic, spiritual and historic value	−/+	−/+[e]	−/+[e]
(14) Recreational potential	− −	− −[e]	− −[e]
(14) Science and education	− −	−[e, f]	−[e, f]

[a]Sub-functions refer to components of the main ecosystem functions, which may change independently of one another. Numbers in parentheses correspond to main functions listed in Table 1.
[b]− indicates increased emissions (negative effect on ecosystem function), + indicates decreased emissions (positive effect on ecosystem function).
[c]− corresponds to decreased soil uptake.
[d]Strongly dependent on location and soil type: very high infiltration under frond piles and on sandy soils (Banabas *et al.*, 2008).
[e]Plantation age not specified in the research study.
[f]Prediction based on reasoning, but no direct data to support this.
[g]Biological control function largely unclear, because highly context-dependent and dependent on spread of pest species.

energy and momentum fluxes, albedo and water-regulating mechanisms (Bonan, 2008). Gas and climate regulation is one of the most studied ecosystem functions in the context of oil palm expansion (Table 1). Most available studies focused on emissions of GHGs and volatile organic compounds (VOCs), a precursor to tropospheric ozone, from oil palm plantations. The replacement of forest by oil palm plantations represents a large loss in gas and climate regulation function (see below). Typically, the carbon sequestered by oil palms does not balance out the GHGs emitted as a result of land-clearing fires and GHG emission from fallow land and plantation establishment (Fargione *et al.*, 2008). Also, VOC emissions from oil palms are higher than for forests and can lead to reduced air quality (Fowler *et al.*, 2011). Land-clearing fires for oil palm cultivation create severe air pollution episodes (Langmann *et al.*, 2009; Marlier *et al.*, 2013), colloquially referred to as haze. These air-pollution episodes are particularly strong during El-Niño Southern Oscillation (ENSO) events, when drier conditions prevail. During fire periods, VOC emissions increase (Muraleedharan *et al.*, 2000), as well as GHGs and aerosol particles, resulting in direct and indirect modifications of solar irradiation (Langmann *et al.*, 2009). Additionally, the different structure of oil palm plantations compared to forest leads to different local microclimatic conditions resulting in higher air and soil temperature and lower air humidity in oil palm plantations compared to forest (Hardwick *et al.*, 2015; Drescher *et al.*, 2016).

(*a*) *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 stages of the land-use change including land clearing, peat drainage (if applicable), and young oil palm stages and typically results in lower carbon stored and a negative GHG balance compared to forests (Fargione *et al.*, 2008). 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; Melling, Hatano & Goh, 2005*a,b*, 2007; 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).

Land-clearing fires lead to large releases of CO_2, both from vegetation and soil (Fargione *et al.*, 2008). Land needs to be cleared to establish oil palm plantations, and fires are the main form of land clearing in Indonesia (Kim *et al.*, 2015). While a small fraction of the carbon in burned vegetation is stored long-term as biochar/charcoal, most is released. The conversion of forest on mineral soil to oil palm plantation results in mean carbon losses of 702 ± 183 (S.D.) Mg CO_2 ha^{-1} over 30 years (Fargione *et al.*, 2008), while conversions on peatlands lead to carbon losses of 1486 ± 183 (S.E.M.) Mg CO_2 ha^{-1} over 25 years (Murdiyarso, Hergoualc'h & Verchot, 2010) to 3452 ± 1294 (S.D.) Mg CO_2 ha^{-1} over 30 years (Fargione *et al.*, 2008). CO_2 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 0.81–2.57 Pg C (Page *et al.*, 2002). Fires can also indirectly increase emissions by exposing organic-rich soil layers to rapid decomposition (Ali, Taylor & Inubushi, 2006) and producing ash, which speeds up peat decomposition (Murayama & Bakar, 1996).

Large amounts of CO_2 are released when peat soils are drained to establish plantations and thus are allowed to oxidize and decompose: estimates range from 26 to 146 Mg CO_2 ha^{-1} $year^{-1}$ (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} $year^{-1}$ (Couwenberg, Dommain & Joosten, 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} $year^{-1}$ 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} $year^{-1}$, 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.*, 2011*a*). 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, Denich & Vlek, 2000; Ishizuka *et al.*, 2005) 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 increased soil disturbance and temperatures (Aweto, 1995; Sommer *et al.*, 2000), decreased leaf litter input (Lamade & Boillet, 2005), and increased soil respiration (Ishizuka *et al.*, 2005; Lamade & Boillet, 2005; Melling *et al.*, 2005*b*). However, the extent of soil carbon loss 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 & Boillet, 2005).

Oil palm plantations, like any vegetation, assimilate CO_2 from the atmosphere, acting as a carbon sink. Overall, oil palm plantations assimilate more CO_2 and produce more biomass per hectare each year than forests due to very high fruit production (Lamade & Boillet, 2005; Kotowska *et al.*, 2015). This high productivity is often used as an argument in favour of oil palm cultivation. However, unless very long timescales are considered, this higher rate of carbon uptake does not make up for the carbon released when forests are cleared for oil palm cultivation, as forests have more aboveground and belowground biomass than oil palm plantations (Germer & Sauerborn, 2008; Kotowska *et al.,* 2015); while tropical rainforests typically store 145 ± 53 Mg C ha^{-1} (Pan *et al.,* 2013), estimations for the time-averaged carbon stock of oil palm plantations range between 36 and 91 Mg C ha^{-1} (Tomich *et al.,* 2002; Henson, 2003, cited in Bruun *et al.,* 2009).

Oil palm plantations also release more N_2O into the atmosphere than forests, mainly due to nitrogen (N) fertilizer use (Murdiyarso *et al.,* 2002; Melling *et al.,* 2007; Fowler *et al.,* 2011; Schrier-Uijl *et al.,* 2013). How N_2O emissions increase after fertilizer application in relation to increases in CO_2 uptake remains unclear (Murdiyarso *et al.,* 2010). Additionally, high spatial variability in N_2O emissions is observed due to fertilization usually being applied directly around the palms and not homogeneously over the plantations (Fowler *et al.,* 2011). Soil texture plays an important role for N_2O emission as well (Sakata *et al.,* 2015).

Methane emissions 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.,* 2005*a*), while on mineral soils this conversion has been shown to reduce CH_4 uptake (Hassler *et al.,* 2015). CH_4 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 GHG emissions (Page *et al.,* 2011*a*). On mineral soils, Fowler *et al.* (2011) and Ishizuka *et al.* (2005) found only small fluxes of CH_4 both in forest and oil palm plantations.

(*b*) *Air quality*

Oil palm plantations affect local and regional air quality mainly in two ways: air pollution from land-clearing fires, and increased emissions of VOCs. 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 & Jessup, 2006). Forest fires release carcinogens and toxic gases such as CO, O_3, NO_2 and particulate matter, decreasing air quality (Reddington *et al.,* 2014) and causing immediate respiratory problems (Mott *et al.,* 2005) as well as long-term health problems (Ostermann & Brauer, 2001; Kamphuis *et al.,* 2010; Schrier-Uijl *et al.,* 2013) and increased mortality (Johnston *et al.,* 2012). In addition, fires add black carbon to the atmosphere, which might enforce global warming (Fargione, Plevin & Hill, 2010).

Oil palms are a major emitter of the VOC isoprene (Misztal *et al.,* 2011), and in general produce more VOCs than forests (Fowler *et al.,* 2011). While the relationships between VOC concentrations, 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 as well (e.g. where traffic volume is high; Sheil *et al.,* 2009; Fowler *et al.,* 2011; Pyle *et al.,* 2011). Studies have measured similar ozone concentrations 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 plantations indirectly affects regional and global climate (Misztal *et al.,* 2011).

(*c*) *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, drier, and allow more light penetration. A recent study in Borneo found that mean maximum air temperatures were up to 6.5°C warmer in oil palm plantations than in primary forests, and up to 4°C warmer in oil palm plantations than in logged forests, with large differences in air moisture content and soil temperature as well (Hardwick *et al.,* 2015). This effect is more pronounced in young (compared to mature) oil palm plantations (Luskin & Potts, 2011), because of their lower canopy cover and lower leaf area index.

(*d*) *Mitigation*

The most effective possible action to reduce GHG emissions related to oil palm cultivation 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 and enforcing the current moratorium on new concessions in primary forests (Austin *et al.,* 2015). Rehabilitation and restoration of converted peatlands is also an option (Table 3). On mineral soils, limiting flooding may prevent increased CH_4 emissions (Schrier-Uijl *et al.,* 2013). Reducing nitrogen fertilizer use can reduce nitrogen-based emissions (N_2O, NO_x, see Table 3). Negative microclimatic effects associated with clear-cutting senescent plantations can be mitigated by sequential replanting that leaves a range of palm ages and maintains canopy cover (Luskin & Potts, 2011). Finally, considering that land-clearing fires continue to be used despite being outlawed in Malaysia and Indonesia,

Table 3. Potential mitigation options for retaining and improving ecosystem functions in oil palm plantations

Mitigation options	Ecosystem functions improved[a]	Source(s)
Protect high-carbon and high-biodiversity areas		
No new concessions in primary forest; no development of plantations on peat land	GC, MEE, P, RN, MR, GR, OR	Yule (2010) and Austin *et al.* (2015)
Enhance enforcement of burning prohibitions and forest moratorium policy	GC, MEE, RN	Environment Conservation Department (2002)
Rehabilitate developed peatlands		
Keep water table as high as possible and rewet soil	GC, MEE	Hooijer *et al.* (2010), Couwenberg *et al.* (2010) and Othman *et al.* (2011)
Maintain ground cover on peat to reduce soil temperature and decrease decomposition rates	GC, WT	Hooijer *et al.* (2012) and Jauhiainen *et al.* (2012)
Maintain a hydrological buffer zone around plantations to protect neighbouring peatlands	GC, MEE	Page, Rieley & Banks (2011*b*)
Compact peat soil to reduce oxidation and decomposition prior to planting (but planting on peat soil should be avoided)	GC	Schrier-Uijl *et al.* (2013)
Improve fertilization practices		
Plant a leguminous ground cover	GC, WRS, SF	e.g. Agamuthu & Broughton (1985)
Use composted plantation and mill waste as fertilizer	GC, WRS, SF, WT	Griffiths & Fairhurst (2003) and Comte *et al.* (2012)
Use slow-release coated fertilizers	GC, SF	*sensu* Akiyama, Yan & Yagi (2010)
Nutrient models, guidelines, and foliar sampling to maximize efficiency of fertilizers	GC, WRS, SF	Comte *et al.* (2012)
Careful application of fertilizer, accounting for soil type, slope, landform, and weather to minimize nutrient leaching losses	GC, WRS, SF	Goh, Härdter & Fairhurst (2003)
Improve hydrological practices, soil conservation practices and protection of microclimate		
Plant herbaceous ground cover to slow run-off and increase infiltration, and reduce erosion	WRS, MEE, SE, SF, WT	Department of Irrigation & Drainage (1989), Fairhurst (1996) and Banabas *et al.* (2008)
Use mulch from plantation wastes (e.g. empty fruit bunches, palm fronds) to slow run-off, increase infiltration, and reduce erosion	WRS, MEE, SE, WT	e.g. Maene *et al.* (1979), Department of Irrigation & Drainage (1989), Fairhurst (1996), Banabas *et al.* (2008) and Stichnothe & Schuchardt (2010)
Maintain hydrological buffers around streams and use silt-pits and foothill drains to prevent sediment and pollution from entering streams	WRS, WT, SE, SF	Haag & Kaupenjohann (2001), Pennock & Corre (2001), Environment Conservation Department (2002) and Comte *et al.* (2012)
Avoid establishment in flood plains and areas prone to flooding	WRS, MEE, RN	Abram *et al.* (2014)
Limit flooding on mineral soils	GC	Schrier-Uijl *et al.* (2013)
Leave areas with slopes >25% with natural forest cover intact and use terracing to reduce soil erosion when applicable	MEE, SE	Dorren & Rey (2004), Murtilaksono *et al.* (2011), Walsh *et al.* (2011) and de Blécourt *et al.* (2014)
Minimize the amount of time that soil is bare	WRS, SE	Environment Conservation Department (2002)
Replant plantations sequentially to protect microclimatic conditions	GC	Luskin & Potts (2011)
Improve biodiversity practices		
Use integrated pest management and replace pesticides with biological pest control and herbicides with manual weeding when possible	WRS, P, BC, GR	Caudwell & Orrell (1997), Ponnamma (2001), Environment Conservation Department (2002) and Yusoff & Hansen (2007)
Increase diversity and structural complexity of vegetation and include areas of native vegetation cover to increase diversity and abundance of species (e.g. decomposers, pollinators, and biological control agents)	WT, P, BC, RN, GR, MR, OR	Caniago & Siebert (1998), Chung *et al.* (2000), Mayfield (2005), Aratrakorn *et al.* (2006), Bhagwat & Willis (2008), Koh (2008*a*), Koh *et al.* (2009), Foster *et al.* (2011) and Azhar *et al.* (2013)
Maintain epiphyte coverage	RN, GR	Koh (2008*b*) and Prescott *et al.* (2015)
Include buffer areas between plantations and forests	RN, GR	Environment Conservation Department (2002) and Koh *et al.* (2009)
Plant polyculture plantations to grow multiple forest products and enhance structural complexity and biodiversity	RN, FRM, GR, MR	Koh *et al.* (2009); but see Azhar *et al.* (2014)
Controlled breeding of oil palms to maintain genetic diversity and local adaptation	GR	Corley & Tinker (2003)
Protect areas and species of spiritual, cultural, or historic importance	IF	Colchester *et al.* (2011)
Require that sufficient habitat remains for endemic species and genotypes	RN, GR, IF	Yule (2010)
Improve waste management		
Treat organic wastes from oil palm plantations (e.g. to produce other products or energy)	WT	e.g. Stichnothe & Schuchardt (2010)

[a]BC, biological control; FRM, food & raw materials; GC, gas & climate regulation; GR, genetic resources; IF, information functions; MEE, Moderation of extreme events; MR, medicinal resources; OR, ornamental resources; P, pollination; RN, refugium & nursery functions; SE, (soil) erosion prevention; SF, soil fertility; WRS, water regulation & supply; WT, waste treatment.

enforcement needs to be enhanced. It is unclear whether such fires could be eliminated entirely, but at the very least, limiting the area that is burned daily would help in reducing the air pollution impacts (Environment Conservation Department, 2002).

(*e*) *Research gaps*

The best available estimates of gas fluxes from oil palm plantations are based on only a few measurements from short-term studies using techniques which are not always representative of the whole ecosystem (i.e. chamber measurements which only consider soil GHG fluxes but not whole-ecosystem fluxes, and with insufficient replicates to cover soil heterogeneity). In addition, more data are needed on soil carbon, the role of ground-cover plants, emissions from drainage canals and ponds in plantations, and on CH_4 and N_2O emissions (Lamade & 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 change, but have received little attention.

(2) 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 water yield (the total amount of water flowing out), 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, Chan & Katimon, 2007). Oil palms have been found to be susceptible to drought, and irrigation can be used to increase their productivity during dry periods by improving the sex ratio (female/total inflorescence production) and reducing the abortion of immature inflorescences (Carr, 2011). Drip irrigation and micro-sprinklers are considered to be suitable methods for irrigating oil palm and the best estimates on yield increase are 20–25 kg fresh fruit bunches ha^{-1} mm^{-1} even if these effects on yield are only seen after 3 years (Carr, 2011). However, irrigation may also contribute to the depletion of aquifers and increase water scarcity (Famiglietti, 2014).

(*a*) *Water storage and supply*

Water storage in oil palm plantations may be reduced in two ways: through peatland drainage and decreased water infiltration (Merten *et al.*, 2016). This decrease in storage increases the risk of both floods and droughts (see below). Peatlands, like giant sponges, hold large quantities of water. Drained peat is inevitably lost, either quickly to fire or slowly to oxidation, permanently reducing the area's water storage capacity (Andriesse, 1988). 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, leading to floods (Page *et al.*, 2009). Infiltration rates are reduced through soil compaction, e.g. due to land clearing, heavy machinery, or traffic (Bruijnzeel, 2004; Rieley, 2007; Banabas *et al.*, 2008). Reduced infiltration rates lead to surface run-off and reduced groundwater recharge, resulting in an amplified catchment response to rainfall events, e.g. increased peak discharge and decreased time-to-peak (Department of Irrigation & Drainage, 1989; Bruijnzeel, 2004).

This increases the risk of floods (Rieley & Page, 1997; Bruijnzeel, 2004; Bradshaw *et al.*, 2007; Rieley, 2007), although the magnitude of the difference 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 floods (i.e. peat soils; Clark *et al.*, 2002; Rieley, 2007; Tan *et al.*, 2009). Young oil palm plantations also have much higher annual water yields than forests and the difference can be extreme (e.g. 270–420% increase in Malaysia; Department of Irrigation & Drainage, 1989). Water yield is increased through a decrease in evapotranspiration (Rieley, 2007; Ellison, Futter & Bishop, 2012) and reduced infiltration rates. There are few comparable studies on evapotranspiration of oil palm plantations of different ages but studies on mature oil palm plantations found evapotranspiration rates to be similar to those of forested catchments (1000–1300 mm $year^{-1}$ for oil palms *versus* 1000–1800 mm $year^{-1}$ for lowland forests; Bruijnzeel, 2004; Comte *et al.*, 2012).

While overall water yield is increased, baseflow (streamflow coming from groundwater) is decreased, leading to greater variability in water yields (Bruijnzeel, 2004). For example, baseflow accounted for 54% of streamflow in oil palm plantations (Yusop *et al.*, 2007) but 70% of streamflow in forests (Abdul Rahim & Harding, 1992). 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; Adnan & Atkinson, 2011). The decreased dry-season flow increases the risk of drought, and on peat soils this risk is amplified by the loss of water storage due to peat drainage (Clark *et al.*, 2002; Rieley, 2007; Tan *et al.*, 2009).

(*b*) *Water quality*

Sediment run-off 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 run-off in plantations. For example, in one study, sediment loads increased from below 50 Mg km^{-2} $year^{-1}$ in forest to 400 Mg km^{-2} $year^{-1}$ immediately after clearance (Department of Irrigation & Drainage, 1989). The establishment of ground cover decreases this impact but sediment loads in water bodies remain higher than in forest: in the Department of Irrigation & Drainage (1989) study, sediment loads dropped only to 100 Mg km^{-2} $year^{-1}$ after legume cover was established. This soil loss can be a severe threat to aquatic ecosystems (Edinger *et al.,* 1998; Bilotta & 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, Ismail & Van Wijk, 1997). In addition, peat drainage reduces the ability of peatlands to act as a freshwater buffer, allowing salt water to intrude (Silvius & Giesen, 1992, cited by Silvius, Oneka & Verhagen, 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 water quality and aquatic organisms (Bilotta & Brazier, 2008; Kemp *et al.,* 2011; Gharibreza *et al.,* 2013). In addition, streams and rivers near oil palm mills are often contaminated with palm oil mill effluent (POME) due to leaks (Ahmad, Ismail & Bhatia, 2003). POME has also been shown to have negative effects on aquatic ecosystems (e.g. due to high biochemical oxygen demand; Khalid & Mustafa, 1992).

(*c*) *Mitigation*

The negative impacts of peatland drainage are likely to be irreversible (Comte *et al.,* 2012). In existing plantations, management practices can help improve water regulation and supply (Table 3). Improved hydrological practices help to slow run-off, increase infiltration, and increase groundwater recharge (Table 3). Improved fertilization practices, reduction of pesticides, and reduction of herbicides have the potential to reduce eutrophification and contamination of streams, groundwater, and water bodies (Table 3).

(*d*) *Research gaps*

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 & Isu, 2007). Comparisons of water dynamics of oil palm plantations at different plantation ages also are lacking (Comte *et al.,* 2012). Further study of water dynamics in mature oil palm plantations is needed, as it is unknown if they show the same differences from forest as young plantations (Comte *et al.,* 2012). Another research priority is to determine methods of restoring dry-season water flow (Bruijnzeel, 2004).

(3) Moderation of extreme events

The term 'moderation of extreme events' is equivalent to the term 'disturbance prevention' used by de Groot *et al.* (2002), but the terminology change acknowledges that some disturbances may be necessary for some ecosystems and their functioning. It is defined as the ability of an ecosystem to prevent and mitigate disruptive natural events (de Groot *et al.,* 2002, 2010). Most of the studies we found examined the moderation capacity 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. Flooding and drought were discussed in Section III.2*a*.

(*a*) *Landslides*

The establishment of oil palm plantations is likely to increase the probability of shallow landslides, whereas large, deep landslides (>3 m soil depth) are mostly influenced by geological, topographic, and climatic factors and should not be affected by land use (Ramsay, 1987*a,b*; Bruijnzeel, 2004). It is known that forests reduce the probability of shallow landslides by stabilizing the top metres of soil with their roots (Starkel, 1972; O'Loughlin, 1984), while deforestation increases the risk of landslides on steep terrain (Imaizumi, Sidle & Kamei, 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 hypothesis.

(*b*) *Wildfires*

The establishment of oil palm plantations increases the risk and frequency of wildfires in surrounding areas in many ways (Hope, Chokkalingam & Anwar, 2005; Naidoo, Malcolm & Tomasek, 2009). First, fires used for vegetation clearing greatly increase the risk of accidentally starting wildfires. 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 (e.g. Mackie, 1984; Hardwick *et al.,* 2015). Finally, the establishment of oil palm plantations tends to lead to degradation of surrounding forests. Oil palm plantations may fragment forests. As tree mortality is elevated at forest edges and in small forest fragments, this may increase fuel loads and thus the vulnerability of forests to canopy fires (Mesquita, Delamônica & Laurance, 1999; Laurance *et al.,* 2002; Morton *et al.,* 2013). Fragmentation may also allow an increase in human activities that can start wildfires (Sheil *et al.,* 2009), while roads can facilitate fire igniting and spreading as well (Mackie, 1984).

(c) *Mitigation*

The strategies for reducing the risk of extreme events in and around oil palm plantations are quite straightforward. Measures to increase infiltration and groundwater recharge will help prevent floods and droughts (Table 3). Avoiding draining peatlands, or draining them as shallowly as possible, helps reduce the risks of floods, droughts, and fires. The establishment of oil palms in flood plains and other areas prone to flooding should also be avoided as oil palm is intolerant to inundation (Mantel, Wosten & Verhagen, 2007; Abram *et al.,* 2014). To prevent landslides, Walsh *et al.* (2011) suggest leaving areas with slopes >25% with their natural forest cover intact. Finally, the enforcement of laws against the use of fire to clear land should be improved.

(d) *Research gaps*

We did not find any studies directly addressing the risks of landslides or wildfires in or around oil palm plantations. Drought risks due to meso-climatic effects of land-use conversion need to be studied in the context of oil palms as well.

(4) Erosion prevention

The soil erosion process involves four phases: detachment, breakdown of aggregates, transport/redistribution, and sedimentation. These four phases depend strongly on land cover/land use, parent material, soil texture, landscape position/landform shape, and climate. Sufficient vegetation cover and land use-associated management practices which improve cover and water infiltration can reduce surface run-off and consequently soil erosion (Kosmas, Gerontidis & Marathianou, 2000). Parent material and its position in the landscape influence transport-limited and detachment-limited erosion, and hence the spatial patterns of soil redistribution (Schoorl, Veldkamp & Bouma, 2002). Soil texture affects transport and redistribution of soil, as clay fractions are more easily removed and redistributed over the landscape than the heavier silt and sand fractions (Lal, 2003). Landscape position and landform shape influence transfer of water within and between landscapes which, in turn, controls soil redistribution and sediment deposition (Swanson *et al.,* 1988). Lastly, precipitation intensity as an agent of these four phases of erosion strongly influences transport and sedimentation processes.

One of the drawbacks of loss of sufficient vegetation cover through forest conversion to oil palm (Fig. 1A–C) is increased soil erosion (Guillaume, Damris & Kuzyakov, 2015). When soil erosion and sedimentation alter the biological process of soil organic carbon (SOC) mineralization, vegetation growth, and water and nutrient availability, they can in turn affect redistribution of SOC within the landscape and its net loss from the landscape (Corre *et al.,* 2015). In a recent pan-tropic study, lowland forest conversion to smallholder oil palm plantations caused the loss of, on average, 40% of stored SOC in the original forest soils in the top 0.1-m depth during the first 10 years of conversion, whereafter a steady-state condition of SOC stocks was attained (van Straaten *et al.,* 2015). Moreover, SOC losses from forest conversion to smallholder oil palm plantations were detected even down to 0.5-m depth.

Based on estimates from erosion models, one can expect soil loss from oil palm plantations to be about 50 times greater than in natural forests, which usually have very low annual sediment losses ($<1-2\,\mathrm{Mg\,ha^{-1}}$; Hartemink, 2006; 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. 1A, B), when the land is bare and maximally exposed to wind and water erosion (e.g. Bruijnzeel, 2004; Hartemink, 2005). In addition, land-clearing fires can cause soil to become water repellent (water repellency reviewed in DeBano, 2000), increasing surface run-off and the potential for soil erosion (Sidle *et al.,* 2006). Rates of soil erosion should then decrease with plantation age, as the oil palm canopy closes and the root network develops (Fig. 1D, E), although even in mature plantations the canopy is broken by roads and other infrastructure (Fig. 1D; Hartemink, 2005).

(a) *Mitigation*

Soil erosion can be minimized by soil conservation practices (Table 3) and by good planning before and during plantation establishment, so that soils are left bare for as little time as possible (Environment Conservation Department, 2002). Maene *et al.* (1979) found a threefold reduction in soil loss in a plantation with mulched paths compared to a plantation with uncovered paths. Terracing is a commonly employed management practice, especially in areas with steep slopes, which has been shown to reduce soil erosion and SOC losses in converted landscapes (de Blécourt *et al.,* 2014). For terracing to be effective, it must be well planned, correctly constructed, and properly maintained (Dorren & Rey, 2004). Terraces should be adapted to local conditions and be combined with additional soil conservation practices (see Table 3).

(b) *Research gaps*

Soil erosion and sedimentation model predictions [e.g. landscape process modelling at multi dimensions and scales (LAPSUS); Schoorl, Sonneveld & Veldkamp, 2000; Schoorl & Veldkamp, 2001; Schoorl *et al.,* 2002] could be tested in the field, with emphasis on landscape positions, landforms, and management practices. For example, LAPSUS-based estimates of soil erosion and sedimentation have been successfully used for landscape-scale estimates of net SOC losses in a converted landscape (e.g. Corre *et al.,* 2015). Such tools can be used to inform policies and methodologies, e.g. REDD+ (reducing emissions from deforestation and forest degradation + conservation, sustainable management of forests, and enhancement of forest carbon stocks). Improved methodologies for the estimation of soil loss and

SOC redistribution at the landscape level can reduce costs, e.g. in the implementation and monitoring of the REDD+ program, and increase accuracy of accounting for the benefit of stakeholders (de Koning *et al.,* 2011).

(5) Soil fertility

Soil fertility refers to the provision of sufficient soil nutrients essential for plant growth and the upkeep of nutrient cycles between vegetation and soil. In tropical forest ecosystems, prior to their conversion to oil palm plantations, their high ecosystem productivity is sustained even 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. The subsequent release of nutrients *via* decomposition and mineralization is susceptible to losses through leaching and gaseous emissions, because the magnitude of uptake from the newly established crops is still relatively low (Mackensen *et al.,* 1996; Dechert, Veldkamp & Brumme, 2005). Nutrient 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 and SOC depends on the initial soil fertility of the original forest (Dechert, Veldkamp & Anas, 2004; Allen *et al.,* 2015; van Straaten *et al.,* 2015). 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.,* 2015; Kurniawan, 2016).

(*a*) *Nutrient losses*

Large amounts of nutrients are lost during plantation establishment as a result of forest clearing and the increased soil leaching that follows (Department of Irrigation & Drainage, 1989; Brouwer & Riezebos, 1998). Large amounts are also lost from established plantations through harvest and removal of palm biomass (Hartemink, 2005) and leaching (Goh & Härdter, 2003). For example, drainage leaching fluxes increased for oil palm plantations compared to the original forests (for ammonium, nitrate, dissolved organic carbon, sodium, calcium, magnesium, and total aluminium measured at 1.5 m soil depth at a site near Jambi, Sumatra, Indonesia; Kurniawan, 2016). These increased leaching losses resulted in a 55% decrease in N retention efficiency (defined as $1 -$ N leaching losses $\div$ soil N availability) and a 70% decrease in base cation retention efficiency (defined as $1 -$ base cation leaching losses $\div$ soil exchangeable bases) in the soil under mature oil palm plantations compared to the same soil type under the original lowland forest. This suggests detrimental effects on water quality (see also Section III.2*b*).

(*b*) *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). Fertilization rates in smallholder oil palm plantations are typically very varied depending on available monetary capital and distance to fertilizer suppliers. For example, in Jambi province (Sumatra, Indonesia), smallholders apply 330–550 kg NPK-complete fertilizer ha^{-1} $year^{-1}$, equivalent to 48–88 kg N ha^{-1} $year^{-1}$, 21–38 kg P ha^{-1} $year^{-1}$ and 40–73 kg K ha^{-1} $year^{-1}$, and occasionally lime (200 kg dolomite ha^{-1} $year^{-1}$). Additional sources of N (138 kg urea-N ha^{-1} $year^{-1}$) and K (157 kg K-KCl ha^{-1} $year^{-1}$) are also applied (Allen *et al.,* 2015). Increased fertilization levels lead to increased nutrient leaching losses (e.g. on loam Acrisol soils relative to clay Acrisol soils; Kurniawan, 2016). Leguminous plants are commonly planted during plantation establishment as a cover and can contribute 239 kg N ha^{-1} $year^{-1}$ (Agamuthu & 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). Empty fruit bunches, palm oil mill effluent, 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 ha^{-1} $year^{-1}$ of dry palm fronds containing 125 kg N, 10 kg P, 147 kg K, and 15 kg Mg (Fairhurst, 1996).

(*c*) *Mitigation*

Improved fertilization practices may improve soil nutrient balances and minimize risk of nutrient losses through leaching (Table 3). Unlike pulse rates of applications of mineral fertilizers, leguminous cover crops and mulch/compost release nutrients slowly and may have minimal risk of nutrient loss to drainage leaching or run-off. Maintaining riparian buffers may also help recover leached nutrients, as such areas are characterized by high content of organic matter and soil nutrients as well as strong retention of nutrients (Table 3; e.g. Haag & Kaupenjohann, 2001; Pennock & Corre, 2001).

(*d*) *Research gaps*

More empirical data are needed on nutrient-retention and nutrient-use efficiencies in oil palm plantations. 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 (piles of senesced fronds spread over the whole plantation area or put on inter-rows to facilitate harvest and maintenance works) are lacking, even though such is common practice in both smallholder and large-scale plantations. On-going studies are directly comparing soil nutrient levels and leaching losses in forest and oil palm plantations using a space-for-time substitution approach (M.D. Corre, personal observations).

(6) Waste treatment

Waste treatment refers to the ability of an ecosystem to remove or recycle organic or inorganic waste, or to abate noise. Palm oil production results in large amounts of organic waste, in particular empty fruit bunches and palm oil mill effluent (Stichnothe & Schuchardt, 2010). While there are many studies on the technical aspects of waste treatment, we did not include these in the database. Instead, we focus on those studies relating to the ecosystem functioning aspects of waste treatment. As discussed in Section III.2*b*, oil palm plantations may act as net sources of organic waste to the surrounding environment, although organic wastes from oil palms can also be used to treat a variety of pollutants, including heavy metal pollution (e.g. Ahmad *et al.*, 2011; Vakili *et al.*, 2014). Foster *et al.* (2011) found no difference in litter decomposition rates (organic waste treatment) between oil palm plantations and forests. 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 have lower biodiversity, biomass, and energy uptake of decomposer organisms (Barnes *et al.*, 2014). However, the direction of expected change is unclear, as drier conditions should slow decomposition (Lamade & Boillet, 2005), while warmer conditions should speed decomposition (Aweto, 1995; Sommer *et al.*, 2000).

(*a*) *Mitigation*

Organic wastes from palm oil production can be recycled in oil palm plantations into mulch and compost or can be treated separately with the potential for additional bioenergy production (e.g. Stichnothe & Schuchardt, 2010). Understorey vegetation can help maintain the abundance and species richness of understorey beetles in oil palm plantations (Chung *et al.*, 2000) and therefore may improve decomposition rates of organic matter in oil palm plantations. Riparian buffers may reduce surface water pollution (Table 3).

(*b*) *Research gaps*

There is a clear need for studies of overall waste treatment in oil palm plantations and differences from forests, including comparison of net production (or removal) of organic and inorganic wastes at the plantation and in the surrounding environment. Decomposition is influenced by leaf composition (e.g. Palm & Sanchez, 1990), and the degree to which oil palm plantations result in a systematic change in nutrient composition, lignin content, and polyphenolic concentrations requires additional study. Additionally, the capacity of oil palms relative to forest to abate anthropogenic noise has not been studied.

(7) Pollination

The ecosystem function pollination refers to the pollination of crops and wild plants (Klein *et al.*, 2007; Ollerton, Winfree & Tarrant, 2011). We found only 36 papers on pollination functions provided by oil palm plantations (Table 1 and see online Appendix S3). We note that there are many more papers on oil palms as beneficiaries of pollination, which will only be discussed briefly below. The data available are too incomplete to come to any explicit conclusions about major differences in pollination between forests and oil palm plantations.

(*a*) *Native pollinators*

Compared to forests, oil palm plantations generally support lower species richness and abundances of invertebrate pollinators (Sodhi *et al.*, 2010). Liow, Sodhi & Elmqvist (2001) found lower abundances, but a greater diversity of pollinating bees. However, the data of Liow *et al.* (2001) come from observations along transects of only the lower canopy and shrub layers, which may differ considerably from higher canopy layers. The weedy vegetation in oil palm plantations (and in cropland in general) is predominantly independent of cross-pollination (due to autogamy, and apomixis, as well as wind pollination, mainly in grasses), which makes them independent of pollinator availability (Gabriel & Tscharntke, 2007). Overall status of pollinators and pollination functions within the remaining natural ecosystems, i.e. in forest habitats, may be reduced in the future due to habitat loss, fragmentation, and isolation of habitats (Potts *et al.*, 2010). Further losses of pollinators can be anticipated due to pollution from large-scale fires.

(*b*) *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), *Elaeidobius kamerunicus* has been introduced into South America and Southeast Asia (Vaknin, 2012). Dhileepan (1994) found that in India populations of *E. kamerunicus* decline during the dry season, but without compromising pollinating efficiency. In the absence of any pollinating insects, wind plays an important role in oil palm pollination (Dhileepan, 1994). *Elaeidobius* weevils also pollinate other palm species such as betelnut (*Areca catechu*) and coconut (*Cocos nucifera*) and so, in theory, oil palm plantations may provide pollination functions to neighbouring crops.

(*c*) *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 diversity in oil palm plantations (see Table 3). This should improve pollination rates for both oil palms and insect-pollinated native plants (Mayfield, 2005; Foster *et al.*, 2011).

(*d*) *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. The highest priority, then, should be additional surveys of pollinator abundance and diversity (including insects, birds, and bats) in oil palm plantations and neighbouring forests. The impact of deforestation and forest fragmentation and isolation, as well as the use of fire for clearing, needs to be assessed in terms of its local and landscape-scale effects on native pollinators and pollination. The potential for oil palm plantations to decrease the pollination function in surrounding native habitat patches (e.g. isolated forest fragments) also needs attention. It would also be useful to test whether oil palm plantations improve pollination of other neighbouring palm crops, as predicted, or whether pollination is diminished due to loss of native pollinator diversity. The potential importance of native pollinators for oil palm fruit set and whether fluctuations of oil palm fruit set and yield are driven by pollination limitation is still unclear and requires further investigation (T. Tscharntke, personal observations).

(8) Biological control

The ecosystem function biological control refers to the ability of ecosystems to prevent organisms from acting as pests or diseases (e.g. Norris, Caswell-Chen & Kogan, 2003). An organism becomes an agricultural pest or a disease if it causes damage to a crop that is above the economic threshold level (Norris *et al.*, 2010; Peshin & Pimentel, 2014). Globally, 30–40% of potential crop yield is destroyed by pathogens and pests (Oerke, 2006).

(*a*) *Biological control within oil palm plantations*

In oil palm plantations, the main organisms that may act as pests or diseases can be categorized as trunk borers (e.g. *Oryctes rhinoceros*, *Rhynchophorus ferrugineus*), defoliators (e.g. *Metisa plana*, *Setora nitens*), frugivores (*Rattus rattus diardii*), plant suckers (*Zophiuma butawengi*), and wilt diseases (*Ganoderma boninense*; see online Appendix S3). Both trunk borer pests are usually associated with one another and may reduce yield by about 12–80% (Liau & Ahmad, 1995; Chung, Cheah & Ramalingam, 1999). The adult of *O. rhinoceros* initially bores into young oil palm spears through petioles and damages the growing point of the palm. The holes give access to *R. ferrugineus*, which further damages the palm. This in turn produces favourable conditions for *O. rhinoceros* larvae to develop inside the stem. *M. plana* and *S. nitens* are common caterpillars and can cause severe defoliation (up to 29–90% yield losses at high infestation levels; Basri, Norman & Hamdan, 1995; Potineni & Saravanan, 2013). The main mammalian pests are rats (*Rattus tiomanicus*, *R. rattus diardii*, and *R. argentiventer*), which can reach densities of 600 ha^{-1} and reduce yields by 5–10% by consuming the mesocarp (Wood & Fee, 2003; Fitzherbert *et al.*, 2008). Damage from the planthopper, *Z. butawengi*, has not yet been quantified, but may be substantial. It is characterized by chlorosis of fronds (Finschhafen disorder) and may kill palms (Woruba *et al.*, 2014). Finally, *G. boninense* is a disease of old palms and can reduce yields by around 50–80% ha^{-1} by restricting water absorption (Priwiratama & Susanto, 2014).

Many of these species could be targeted by biological control. There is limited knowledge of the differences in biological control between oil palm plantations and forests (Savilaakso *et al.*, 2014). 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 local practices such as pesticide applications and clearance of the understorey as well as the simplification of the surrounding landscape (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 habitat resources (Chung *et al.*, 2000; Donald, 2004; Koh, 2008*a*; Bateman *et al.*, 2009; Koh, Levang & Ghazoul, 2009). For instance, insectivorous birds and bats, known as major biocontrol agents for a number of pests (Maas, Clough & Tscharntke, 2013), have difficulty adapting to oil palm plantations, resulting in higher pest attacks, and potentially reduced crop yield (Aratrakorn *et al.*, 2006; Koh, 2008*a*,*b*). Compared to forests, the majority of birds and bats are lost in oil palm (Aratrakorn *et al.*, 2006; Shafie *et al.*, 2011). Low population size and diversity of predatory beetles might explain the high density of chrysomelid pests in oil palm plantations (Chung *et al.*, 2000).

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

(*b*) *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 of these pests in oil palm plantations. For instance, rhinoceros beetles and planthoppers are also pests of coconut (Huger, 2005; Gitau *et al.,* 2011; Guerrieri *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 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, Meon & Yun, 2010), and palm oil reduces beetle incidence in maize, sorghum, and wheat grains (Kumar & 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 *Clidemia hirta* into forest (Fujinuma & Harrison, 2012).

(*c*) *Mitigation*

By definition, the use of integrated pest management practices instead of chemical pesticides alone increases the provisioning of biological control in oil palm plantations. Management practices that increase diversity (especially of arthropods and birds) in oil palm plantations (see Table 3, but see also Teuscher *et al.,* 2015, for a cost–benefit analysis) may also increase the provisioning of biological control – native insectivorous birds, for instance, could reduce herbivory on oil palms (Aratrakorn *et al.,* 2006; Koh, 2008*a*).

(*d*) *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 to maintain robust biological control agent populations. There is a need for basic surveys of biodiversity in oil palm plantations and 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 (2008*a*). 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 surrounding plantations, and growing flowering plants in the understorey, as flowering plants may provide supplemental food resources when prey are scarce (e.g. Basri *et al.,* 1995). 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 (e.g. Blitzer *et al.,* 2012; Lucey *et al.,* 2014).

(9) **Refugium & nursery functions**

These functions refer to the ability of an ecosystem to provide habitats that meet species' needs and thus allow them to survive and reproduce. These functions are crucial for the maintenance of biodiversity and associated services (Tscharntke *et al.,* 2012*a*; see also Section I.3). Oil palm plantations have a simpler structure than forests: their canopy is much lower, the upper canopy comprises only one species, and other plant growth forms such as lianas are completely absent or reduced (Danielsen *et al.,* 2009; Foster *et al.,* 2011; Luskin & Potts, 2011). Furthermore, the understorey of oil palm plantations is hotter, drier, and receives more light than the forest understorey (Hardwick *et al.,* 2015; Drescher *et al.,* 2016). As a result, oil palm plantations are lacking the specific environmental conditions required by many forest species. Furthermore, due to high levels of disturbance and propagule pressure, 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).

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) in two important ways. First, plantation development usually increases access to forest areas, leading to increased utilization and higher 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, increased invasion of non-native species, reduced species movement, greater population isolation, and greater risks of local and global extinction (Campbell-Smith *et al.,* 2011; Fujinuma & Harrison, 2012).

The ability of oil palm plantations to provide habitat depends on plantation age (Luskin & Potts, 2011) and management intensity (Teuscher *et al.,* 2015). Habitat quality should increase with plantation age, as the canopy closes and structural complexity increases (Luskin & Potts, 2011), although the trend is not so clear for birds (Azhar *et al.,* 2011). Management practices in oil palm plantations, with respect to available riparian and terrestrial habitats, mainly determine anuran species composition in oil palm plantations (Faruk *et al.,* 2013; Norhayati, Ehwan & Okuda, 2014). In addition, there is some evidence that biodiversity is higher in smallholder than in large-scale plantations, at least for birds (Azhar *et al.,* 2011). Within smallholder plantations, Teuscher *et al.* (2015) have shown that the density of native trees has a positive effect on bird diversity and abundance.

(*a*) *Mitigation*

The habitat functions of oil palm plantations can be improved by changing management practices in planted areas and by maximizing unplanted areas maintaining native vegetation (see Table 3, but see also Edwards *et al.,* 2010). In planted areas, management for biodiversity hinges on increasing the diversity and structural complexity of vegetation – through increasing the height, coverage, and diversity of ground-cover plants, planting tree species, and letting epiphytes thrive (Koh, 2008*b*; Koh *et al.,* 2009). Management practices that harm biodiversity (e.g. epiphyte removal) may result in costs with no benefit to yield (Prescott, Edwards & Foster, 2015). Unplanted areas can also act as a buffer zone to reduce impacts on adjoining forest areas.

(*b*) *Research gaps*

Refugium and nursery functions are still underappreciated in biodiversity research. They require a landscape perspective that includes assessments of edge effects, landscape configuration, and species' patch size requirements (Zurita *et al.,* 2012). More research into the role of increasing dissimilarity of community composition with distance is needed as well, considering that small patches over a large distance may harbour many more species than one, spatially restricted large patch (Tscharntke *et al.,* 2012*b*; but see Edwards *et al.,* 2010). 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 (e.g. jungle rubber, scrubland, rubber plantations or secondary forest) on community composition and ecological functioning inside oil palm plantations has been neglected so far (but see Edwards *et al.,* 2014*b*). Smoke from land-clearing fires has been shown to cause serious human health problems (Aiken, 2004), and impacts of smoke-related pollution on wildlife habitat need to be addressed. Finally, the links between the Refugium & nursery functions and other functions and services must be explored within a multi-scale context and in consideration of the long-term effects of gradual degradation of remaining forest habitats.

(10) 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. Oil palm may also contribute to local food insecurity when land is taken from rural or indigenous communities for commercial oil palm production (Nesadurai, 2013) or when palm oil is used for biofuels instead of food (Ewing & Msangi, 2009).

(*a*) *Foods and materials from oil palm*

Oil palm outperforms other oil crops such as rapeseed and soy by 3–8 times in production per hectare (Sheil *et al.,* 2009). Oil palm plantations produce an average of 3–4 Mg ha^{-1} year^{-1} of oil, with some commercial plantations producing around 7 Mg ha^{-1} year^{-1}, and improved varieties and management could result in yields over 10 Mg ha^{-1} year^{-1} (Wahid *et al.,* 2005). Palm oil is the main output of oil palm plantations, with crude palm oil mainly being used in food and palm kernel oil in the production of detergents, cosmetics, plastics, and chemicals (Wahid *et al.,* 2005). Palm kernel meal and POME can be used for animal feed. Livestock can graze in oil palm plantations and intercropped plantations can also produce a range of other food crops (Corley & Tinker, 2003, pp. 265–269). However, these practices generally take place before plantations reach full maturity. In Africa, oil palm sap is extracted, fermented, and distilled into palm wine (Corley & Tinker, 2003). Oil palm trunks can be made into furniture (e.g. Suhaily *et al.,* 2012), and other waste products (empty fruit bunches, leaves, fruit shells, and fibres) can be used to make a variety of products (e.g. paper, activated carbon, and fish food; Ahmad, Loh & Aziz, 2007; Bahurmiz & Ng, 2007; Wanrosli *et al.,* 2007). Oil palm products can also be used as fuels (e.g. Harsono *et al.,* 2012), POME can be fermented to produce methane/biogas (Yacob *et al.,* 2006), and oil palm waste products can be burned directly (Yusoff, 2006). Finally, pigs, snakes, and rats, often considered as pests, may be hunted in oil palm plantations for food (Luskin *et al.,* 2014; K. Darras, personal observations).

(*b*) *Loss of forest foods and materials*

Forests support many species that oil palm plantations do not, including many species used for food and raw materials (e.g. construction materials, fuelwood, resins; Shackleton, Delang & Angelsen, 2011). Such timber and non-timber forest products are especially important during times of crop failure (Sheil *et al.,* 2006; Shackleton *et al.,* 2011). In addition, forests in many regions are used for the cultivation of rattan and jungle 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 societies (Belcher *et al.,* 2004; Sheil *et al.,* 2006).

(*c*) *Mitigation*

Some forest plants could potentially be cultivated in oil palm plantations to prevent the loss of some forest products. However, many forest products will be entirely absent from harvestable oil palm plantations.

(*d*) *Research gaps*

This is a well-researched ecosystem function for oil palm plantations and our database only reflects a fraction of the 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). A summary of active research topics is given by Corley & 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 are needed – including monetary and non-monetary valuation of forest resources.

(11) Genetic resources

Genetic resources refer to the genetic material of organisms present in an ecosystem including the potential for future evolution (modified from de Groot *et al.,* 2002). The importance of genetic resources for 'food security, public health, biodiversity conservation, and the mitigation of and adaptation to climate change' is internationally recognized (Nagoya Protocol, 2011). In general, oil palm agriculture can impact genetic resources in two important ways. First, as conversion of forest to oil palm plantations greatly reduces species richness and species' abundances for most taxa (see Section I.3), genetic resources at the assemblage level are most likely greatly reduced in oil palm plantations. Consequently, the long-term viability of forest plant and animal populations is expected to be negatively affected in oil palm landscapes due to the extinction of rare alleles and reduced gene flow between isolated forest fragments (Vellend, 2003), as recently shown for Malaysian ants (Bickel *et al.,* 2006) and bats (Struebig *et al.,* 2011). Second, genetic resources are further reduced because the oil palms themselves are derived from genetically limited sources (Thomas, Watson & Hardon, 1969; Corley & Tinker, 2003). With clonal propagation of oil palms, genetic variation is expected to decrease even further due to the planting of high-yield clones (Corley & Tinker, 2003). However, genetic variability in oil palms has attracted considerable research (e.g. Cochard *et al.,* 2009), and natural genetic variation exists. Several organizations, such as the Malaysian Palm Oil Board, maintain oil palms of a variety of genetic origins (Hayati *et al.,* 2004). In sum, genetic resources are critical to maintaining global biodiversity and to maintaining high yields from oil palm plantations.

(*a*) *Mitigation*

Much of the loss of genetic resources due to the loss of species and decreases in species abundances cannot be mitigated. Mitigation measures for biodiversity loss (see Table 3) will also help to maintain genetic resources. On-going breeding programs can make conservation of oil palm genetic diversity a priority (Corley & Tinker, 2003). Breeding can be carried out selectively to maintain genetic diversity while still preserving local co-adapted traits (Corley & Tinker, 2003). In addition, genetic modification has been suggested to have the potential to increase yield and resistance to disease and stress (Corley & Tinker, 2003).

(*b*) *Research gaps*

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

(12) Medicinal resources

This function refers to medicinal resources derived from the organisms in an ecosystem. An estimated 52885 flowering plant species are used today worldwide for medicinal purposes (Schippmann, Leaman & Cunningham, 2002) and over 2000 Southeast Asian forest species are used in women's healthcare (de Boer & Cotingting, 2014). In Kalimantan, Indonesian local healers use more than 250 medicinal plants of which Caniago & Siebert (1998) found the most in old secondary forest (79 species) and the fewest in logged areas (18 species), concluding that land degradation and forest conversion reduce the availability of medicinal plants. Mathews, Yong & Nurulnahar (2007) surveyed oil palm plantation ecosystems and identified 48 species of medicinal value, many of which were common generalist species. Many of these are considered weeds, and are actively removed (Sarada, Nair & Reghunath, 2002; Mathews *et al.,* 2007). However, the conversion of forests to oil palm plantations leads to an impoverishment of the biotic community (Danielsen *et al.,* 2009, see Section I.3) and with that to an overall loss of medicinal resources. Consequently, the expansion of oil palm plantations represents a loss in this function at local, regional, and global scales compared to forest.

(*a*) *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 & Osborne, 2000) and to cure colds and bad coughs (Macía, 2004). Traditional use of leaf extract has led to its study for wound-healing and antimicrobial properties (Chong *et al.,* 2008; Sasidharan *et al.,* 2010; Sasidharan, Logeswaran & Latha, 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; Caniago & Siebert, 1998; Chong *et al.,* 2008).

(*b*) *Mitigation and research gaps*

Measures to mitigate the loss of medicinal resources will be difficult as the medicinal properties of many species remain unknown, especially for species unknown to science. 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 respected medical journals.

(13) Ornamental resources

Ornamental resources are the variety of organisms in ecosystems with potential ornamental use (e.g. as garden plants, pets, or jewellery; definition modified from de Groot *et al.,* 2002). This includes organisms collected for domestic purposes (predominantly bird species; Nash, 1993), or for international trade (Ng & Tan, 1997; Sodhi *et al.,* 2004; New, 2005; Nijman, 2010; Phelps & Webb, 2015), in particular plants (especially orchids), invertebrates (bird spiders, scorpions, stick insects, rhino beetles, butterflies, and moths), and vertebrates (fish, amphibians, reptiles, birds and mammals). Very few studies on this topic were found (Table 1), as most studies instead focus on the over-exploitation of species used for ornamental purposes (e.g. Nijman, 2010), and much of the trade is illegal (e.g. Phelps & Webb, 2015). Ornamental resources have been found to decrease in cultivated land relative to forests (Sheil & Liswanti, 2006). Changes in hydrology due to the drainage of peat land for the cultivation of oil palm plantations has led to population decreases of some economically important ornamental fish species, e.g. *Betta* spp. and the arowana, *Scleropages formosos*, despite these species being bred commercially (Ng & Tan, 1997; Yule, 2010; Posa, Wijedasa & Corlett, 2011). A few ground-dwelling python species used in the pet trade (i.e. *Python brongersmai*, *P. curtus*, *P. breitensteini*) and several rat snake species (e.g. *Ptyas* spp.) and cobras (e.g. *Naja sumatrana*, *N. sputatrix*) harvested for their skins and medicinal purposes, largely benefit from oil palm plantations (Whitten *et al.,* 1984; Shine *et al.,* 1999; Auliya, 2006) due to high rodent densities attracted to palm fruit (Buckle *et al.,* 1997). However the commercial offtake and trade for their skins and medicinal uses is many times over that of the pet trade (see CITES, 2015). Keeping caged pet birds is a common practice and an important part of Indonesian culture (Jepson & Ladle, 2009), and there is evidence of bird trapping from oil palm plantations (K. Darras, personal observations). Based on preliminary results of an ongoing bird market survey in Jambi city, Indonesia, the majority of birds are collected from forests (33 species from forest compared to 15 species in oil palm, only two shared; K. Darras & T. Tscharntke, personal observations). Despite decreasing forest cover and decreasing accessibility to forests, oil palm supplies considerably fewer birds at lower prices than do forests, representing a decrease in the ornamental resources ecosystem function.

(*a*) *Mitigation and research gaps*

Overall, it appears that the ornamental resources in forests are greater than in oil palm plantations and irreplaceable in the case of birds, and this is likely true for many other taxa as well. More research is needed to understand the separate and combined effects of the oil palm industry and the trade in ornamental species on the availability of ornamental resources, their viability, and long-term sustainability.

(14) Information functions

Information functions provide 'opportunities for cognitive development' (de Groot *et al.,* 2002), in other words, they provide the basis for rather intangible benefits that people derive from an ecosystem. They are subject to individual perception and valuation and contribute to maintenance of human health. de Groot *et al.* (2002) classify information functions into: (*i*) aesthetic information, i.e. appealing landscape elements; (*ii*) recreation and tourism, constituted through a variety of such landscapes; (*iii*) cultural/artistic inspiration and spiritual/historic information, both inherent in natural features with respective values; and (*iv*) scientific and educational information, i.e. scientific and educational values in nature. In general, the conversion of forest to oil palm cultivation leads to a large loss in information functions.

We discuss all information functions together, as we found only 30 papers relevant to information functions in oil palm plantations (see online Appendix S3). Most of these papers address aesthetic, cultural and artistic, spiritual and historic aspects (23), nine papers treat recreation and tourism, and only six papers address issues of educational and scientific relevance. In part, the under-representation of information functions is due to a focus of research on the socioeconomic benefits of oil palms (e.g. Rist, Feintrenie & Levang, 2010; Hector *et al.,* 2011; Cramb & Curry, 2012; Obidzinski *et al.,* 2012; Lee *et al.,* 2014). Further, few articles address the triad between oil palms, information functions, and forest – the loss of information functions during forest conversion is hardly investigated.

(*a*) *Information functions associated with oil palm and palm oil*

In its native range, locations where oil palms are growing are considered sacred places (Gruca, van Andel & Balslev, 2014). Several parts of the palm, including palm oil, are integrated into local traditions and customs [e.g. local food cultures (Atinmo & 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, Feintrenie & Levang, 2011). However, large oil palm monocultures are typically associated with few information functions (Watkins, 2015).

(*b*) *Information functions lost with forest conversion to oil palm*

Unlike oil palm plantations, forests are valued highly for different reasons (Sheil & Liswanti, 2006; Sheil *et al.,* 2006; Pfund *et al.,* 2011), e.g. health, cultural, and spiritual purposes (Meijaard *et al.,* 2013) and recreational potential (Bennett & Reynolds, 1993; Broadbent *et al.,* 2012; Burke & Resosudarmo, 2012; Ratnasingam *et al.,* 2014). With deforestation for establishment of oil palm plantations and the related depletion of resources, these functions and the so-called 'locality of value' (Nooteboom & de Jong, 2010) likewise disappear. A case study conducted in Indonesia recorded the destruction of the 'ancestral grave which is located in forested groves that is of cultural significance to indigenous people' (Manik, Leahy & Halog, 2013, p. 1390), but note that graveyards can also exist in oil palm plantations (Colchester *et al.,* 2011). Land-use conflicts may also lead to the depletion of information functions (historical and spiritual), as happened in Kalimantan, Indonesia (Potter, 2009).

A closer look at the recreational potential of ecosystems reveals that natural forests support a tourist industry while clearance for oil palm plantations or other land uses reduces the aesthetic qualities and thus the basis for nature-based tourism. For example, Bennett & Reynolds (1993) found a loss of 50% of tourism revenues (3.7 million USD) when mangroves were cleared for ponds and oil palm. Further, tourism presents an alternative income source and is therefore a means to nature conservation (Broadbent *et al.,* 2012) and long-run green growth (Burke & Resosudarmo, 2012). The difference in the appreciation of 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).

(*c*) *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 forest cover of distinct 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.

(*d*) *Research gaps*

Not much research on information functions has been conducted. Consequently, information functions are proportionally under-represented among all ecosystem functions (Table 1). Research has focused on socio-economic benefits, human well-being following land-use change and land-use conflicts, instead of on information functions (following de Groot *et al.,* 2002) or transformation of cultural ecosystem services (see, e.g. Millennium Ecosystem Assessment, 2005).

IV. DISCUSSION

(1) Impacts of oil palm plantations

With few exceptions, oil palm plantations have reduced ecosystem functioning compared to forests (Table 2). The greatest impacts are on gas regulation, water regulation and supply, habitat functions, and information functions. Food and raw material production is the only function that shows a net increase in oil palm plantations. With proper management, it may be possible to maintain some functions at forest levels (water regulation, regulation of extreme events, soil retention, nutrient regulation, and waste treatment).

Evaluating ecosystem functions in oil palm plantations is often not straightforward. First, many functions are interrelated – for instance, poorer water regulation in oil palm plantations can also lead to increased risks of floods and droughts and greater losses of soil and nutrients. Second, ecosystem functions change throughout the life cycle of an oil palm plantation, with greatest losses in functioning when land is cleared for plantation establishment, and a gradual restoration of some functions as plantations mature. Third, ecosystem functions in oil palm plantations depend heavily on plantation management practices, which vary greatly. Fourth, some effects on ecosystem functions are heterogeneous (e.g. N_2O balance, Table 2) and may vary depending on local conditions. Finally, in some cases, contrasting effects on ecosystem functions can be present simultaneously. For example, some species abundances greatly increase while others greatly decrease (Table 2).

(2) Options for mitigation

First, impacts of oil palm cultivation 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 existing agricultural land (Härdter, Chow & Hock, 1997; Yusoff & Hansen, 2007; Reijnders & Huijbregts, 2008). However, debate continues over what land is defined as acceptable for oil palm (Koh & Wilcove, 2008). This includes indirect conversion where cultivated land replaces forest, and oil palm then replaces other cultivated land (i.e. the cascade effect; Lambin & Meyfroidt, 2011). The loss of some forest-specific ecosystem functions cannot be mitigated (e.g. loss of forested areas critical to the persistence of endemic forest-specialist species; Gibson *et al.,* 2011). In order to maintain certain ecosystem functions such as medicinal resources, and habitat and nursery functions, these areas would need to remain uncleared, and cleared areas would need to be restored. The negative impacts of oil palm plantations may also be reduced through improved plantation management (see Table 3). Many mitigation management practices contribute to improving multiple ecosystem functions at once (see Table 3).

(3) Major research gaps

We identified important research gaps for each ecosystem function. Generally, there is a need for comparative studies to identify the influences of plantation age, local environmental conditions, and plantation management on ecosystem functioning within and surrounding plantations. Management practices vary greatly among plantations (Vermeulen & Goad, 2006; Comte *et al.,* 2012), and these factors have largely been neglected. Studies should explicitly consider differences between smallholder and large-scale plantations (Azhar *et al.,* 2011; Harsono *et al.,* 2012; Jambari *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 limited, coarse-scale information on ecosystem functions. Finally, capacity building is required to foster studies by local scientists, who are likely to have the most complete and up-to-date knowledge (Sheil *et al.,* 2009), as well as better access to knowledge held by native and indigenous people.

(4) **Considerations of scale: spatial, temporal, and management**

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 moderation of extreme events functions are decreased. At the landscape scale (plantation and immediate surroundings), microclimate, air quality, water regulation, moderation of extreme events, and erosion prevention are decreased while soil fertility is changed. Aside from additional waste production, the effects on local waste treatment are unclear. The regional and local effects on pollination and biological control are also unclear. Educational and scientific information functions are lost at all scales, due to a loss of species and habitat diversity associated with the loss of forest (e.g. Foster *et al.,* 2011). Local-scale changes may also drive larger-scale effects, especially on climate regulation (droughts) and downstream regions within watersheds (flood risks, nutrient leaching, soil erosion). The landscape context and cross-scale impacts of oil palm plantations thus warrant further research.

Ecosystem functioning also shows strong temporal patterns (Table 2). Most decreases in ecosystem functioning occur with the loss of forest or drainage of peat (i.e. GHG emissions, air quality reduction, water regulation changes, moderation of extreme events, soil retention, and loss of information functions). Some recovery of ecosystem functioning occurs with the establishment of the plantations, including carbon fixation by oil palms and stabilization of soil with establishment of ground cover. Production functions are also dynamic, starting 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). Much of the temporal fluctuation in ecosystem functioning is mediated by plantation management. For example, nutrient regulation depends strongly on fertilizer application and mulching approach (Comte *et al.,* 2012). However, much knowledge is missing about the processes occurring during oil palm ageing and during the replacement of old with new palms. The number of sequential plantings and their dependence on external inputs (nutrients) remains unknown, thus impeding evaluations of long-term functioning and sustainability.

A third scale important to oil palm effects on ecosystem functions is the scale at which management is carried out. However, for many ecosystem functions, the difference in effect on ecosystem functions, if any, between smallholder and large-scale plantations is unknown (e.g. water regulation, soil loss, pollination, biological control).

(5) **Policy considerations**

An accurate assessment of ecosystem functions is essential to the establishment of comprehensive guidelines for protecting natural capital. The findings of this review could be used to assess potential changes in ecosystem functions associated with oil palm plantations. This comprehensive assessment could complement on-going efforts to map ecosystem services (e.g. Barano *et al.,* 2010), and provide a basis for sustainable development policies in regions where oil palm is grown. Official governmental policies, certification schemes, lobbying by industry and non-governmental organizations and consumer choices (e.g. boycotts) all influence oil palm production, and hence ecosystem functions in oil palm plantations. For example, official governmental policy in Indonesia prohibits the clearing of land through burning, but laws are not always enforced (Sheil *et al.,* 2009). Enforcing existing regulations would therefore be a positive step forward. Government policies in importing countries may also influence oil palm production, as some countries have set import standards in response to public pressure (e.g. with respect to biofuels, European Union Renewable Energy Directive; United States Renewable Fuel Standard 2; Lim, Biswas & Samyudia, 2015), although corporations can partially by-pass such restrictions by exporting oil palm products from sustainably managed plantations to countries with import standards, while exporting oil palm products produced unsustainably to other markets (e.g. China and India; Lim *et al.,* 2015).

In order partly to address the limited compliance with existing legislation, Indonesia has now introduced the Indonesia Sustainable Palm Oil (ISPO) certification scheme (mandatory for large plantations as of 2014, and for smallholders by 2020). The ISPO requires that oil palm only be planted on lands for which official legal titles exist, which excludes recently deforested land and peatlands (see http://www.ispo-org.or.id/index.php?lang=en). Whether implementation will indeed proceed as planned is an open question, particularly as implementation is seen as costly to producers and might cause particular challenges for smallholders who often do not have legal titles for their land.

Internationally, oil palm growers can obtain certification from the Roundtable on Sustainable Palm Oil (RSPO, which certified 16% of global palm oil production as of March 2014; Lim *et al.,* 2015) and/or from the International Sustainability and Carbon Certification (ISCC, which as of May 2014 only certified a small part of the market; Lim *et al.,* 2015). The Roundtable on Sustainable Palm Oil (RSPO) is a well-known international voluntary certification scheme which has been in operation since 2004 (Nesadurai, 2013). The RSPO is an internationally recognized standard that focusses on transparency, compliance with laws and regulations, long-term viability, environmental and social responsibility, among other aspects and is attracting an increasing number of producers (see rspo.org). However, RSPO has a mixed record in ensuring environmental sustainability and maintaining biodiversity in oil palm and more needs to be done to strengthen the standard as well as improve compliance (e.g. Paoli *et al.,* 2010; Brandi *et al.,* 2012; Nesadurai, 2013). Finally, public pressure on the oil palm industry, especially from non-government organizations (NGOs) such as Greenpeace, the Rainforest Action Network, and the World Wildlife Fund, has had a strong influence on public policy relating to oil palm plantations (Lim *et al.,* 2015). In summary, existing policies have been insufficient to prevent the loss of many ecosystem functions associated with the establishment of oil palm plantations (Table 2, Fig. 2). It appears that this has been largely due to poor compliance with existing laws, policies, and standards. A more holistic sustainability assessment framework (Lim *et al.,* 2015), including the ecosystem functions highlighted herein and their associated ecosystem services, could serve to correct for deficiencies and further strengthen the existing standards.

V. CONCLUSIONS

(1) This comprehensive review of ecosystem functions in oil palm plantations revealed that 11 of 14 ecosystem functions showed a net decrease in oil palm plantations.

(2) We provide novel reviews of the following ecosystem functions in oil palm plantations: genetic resources, medicinal resources, ornamental resources, and information functions. We highlight that there are critically important knowledge gaps with respect to these neglected but important topics.

(3) We identify research gaps, mitigation options, and highlight mitigation options that improve multiple ecosystem functions simultaneously. With respect to the gaps, most results originate from short-term studies that may not be representative of whole ecosystems. In this respect, we reveal a great need for more comprehensive and long-term studies, with more variables measured, comparing a wider range of environments and management practices.

(4) Ecosystem functions in the regulation, habitat, and information categories tend to decrease in oil palm ecosystems compared to forest as a reference land use. Very large and globally important decreases occur in greenhouse gas regulation, habitat provision, medicinal, genetic, and ornamental resources, and recreational potential. Regionally, water regulation and erosion prevention functions are decreased. The decreasing trends vary depending on plant ages, soil types, and spatial scale. On the other hand, the food and raw materials production function of oil palm is higher compared to that of forest.

(5) For gas and climate regulation, water regulation, moderation of extreme events, and habitat and nursery functions, a key option from an ecosystem function perspective is to preserve peatlands (i.e. maintaining upstream hydrology and completely avoiding drainage; Comte *et al.,* 2012).

(6) By knowing how oil palm affects the degree and the direction of changes in ecosystem functions for each category, strategies can be developed to reduce the degradation of ecosystem functions while maintaining or even increasing socio-economic functioning.

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VII. REFERENCES

Abdul Rahim, N. & Harding, D. (1992). Effects of selective logging methods on water yield and streamflow parameters in peninsular Malaysia. *Journal of Tropical Forest Science* **5**, 130–154.

Abram, N. K., Xofis, P., Tzanopoulos, J. & MacMillan, D. C. (2014). Synergies for improving oil palm production and forest conservation in floodplain landscapes. *PLoS ONE* **9**, e106391.

Achten, W. M. J. & Verchot, L. V. (2011). Implications of biodiesel-induced land-use changes for CO_2 emissions: case studies in tropical America, Africa, and Southeast Asia. *Ecology and Society* **16**, 1–14.

Adnan, N. A. & Atkinson, P. M. (2011). Exploring the impact of climate and land use changes on streamflow trends in a monsoon catchment. *International Journal of Climatology* **31**, 815–831.

Afiff, S. & Lowe, C. (2007). Claiming indigenous community: political discourse and natural resource rights in Indonesia. *Alternatives* **32**, 73–97.

Agamuthu, P. & Broughton, W. (1985). Nutrient cycling within the developing oil palm-legume ecosystem. *Agriculture Ecosystems & Environment* **13**, 111–123.

Ahmad, A. L., Ismail, S. & Bhatia, S. (2003). Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination* **157**, 87–95.

Ahmad, A., Loh, M. & Aziz, J. (2007). Preparation and characterization of activated carbon from oil palm wood and its evaluation on methylene blue adsorption. *Dyes and Pigments* **75**, 263–272.

Ahmad, T., Rafatullah, M., Ghazali, A., Sulaiman, O. & Hashim, R. (2011). Oil palm biomass–Based adsorbents for the removal of water pollutants—A review. *Journal of Environmental Science and Health. Part C* **29**, 177–222.

Aiken, S. R. (2004). Runaway fires, smoke-haze pollution, and unnatural disasters in Indonesia. *Geographical Review* **94**, 55–79.

Akiyama, H., Yan, X. & Yagi, K. (2010). Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis. *Global Change Biology* **16**, 1837–1846.

Ali, M., Taylor, D. & Inubushi, K. (2006). Effects of environmental variations on CO_2 efflux from a tropical peatland in eastern Sumatra. *Wetlands* **26**, 612–618.

Allen, K., Corre, M. D., Tjoa, A. & Veldkamp, E. (2015). Soil nitrogen-cycling responses to conversion of lowland forests to oil palm and rubber plantations in Sumatra, Indonesia. *PLoS ONE* **10**, e0133325.

Allou, K., Morin, J.-P., Kouassi, P., N'klo, F. H. & Rochat, D. (2006). *Oryctes monoceros* trapping with synthetic pheromone and palm material in Ivory Coast. *Journal of Chemical Ecology* **32**, 1743–1754.

Andriesse, J. (1988). *Nature and Management of Tropical Peat Soils*. Food & Agriculture Organization, Rome.

Aratrakorn, S., Thunhikorn, S. & Donald, P. (2006). Changes in bird communities following conversion of lowland forest to oil palm and rubber plantations in southern Thailand. *Bird Conservation International* **16**, 71–82.

Arsic, I., Zugic, A., Antic, D. R., Zdunic, G., Dekanski, D., Markovic, G. & Tadic, V. (2010). *Hypericum perforatum* L. Hypericaceae/Guttiferae sunflower, olive and palm oil extracts attenuate cold restraint stress-induced gastric lesions. *Molecules* **15**, 6688–6698.

Arsic, I., Zugic, A., Tadic, V., Tasic-Kostov, M., Misic, D., Primorac, M. & Runjaic-Antic, D. (2012). Estimation of dermatological application of creams with St. John's Wort oil extracts. *Molecules* **17**, 275–294.

Atinmo, T. & Bakre, A. (2003). Palm fruit in traditional African food, culture. *Asia Pacific Journal of Clinical Nutrition* **12**, 350–354.

Auliya, M. (2006). *Taxonomy, Life History and Conservation of Giant Reptiles in West Kalimantan*. Natur und Tier-Verlag, Münster.

Austin, K. G., Kasibhatla, P. S., Urban, D. L., Stolle, F. & Vincent, J. (2015). Reconciling oil palm expansion and climate change mitigation in Kalimantan, Indonesia. *PLoS ONE* **10**, e0127963.

Aweto, A. O. (1995). Organic carbon diminution and estimates of carbon dioxide release from plantation soil. *The Environmentalist* **15**, 10–15.

Azhar, B., Lindenmayer, D. B., Wood, J., Fischer, J., Manning, A., McElhinny, C. & Zakaria, M. (2011). The conservation value of oil palm plantation estates, smallholdings and logged peat swamp forest for birds. *Forest Ecology and Management* **262**, 2306–2315.

Azhar, B., Lindenmayer, D. B., Wood, J., Fischer, J., Manning, A., McElhinny, C. & Zakaria, M. (2013). The influence of agricultural system, stand structural complexity and landscape context on foraging birds in oil palm landscapes. *Ibis* **155**, 297–312.

Azhar, B., Puan, C. L., Zakaria, M., Hassan, N. & Arif, M. (2014). Effects of monoculture and polyculture practices in oil palm smallholdings on tropical farmland birds. *Basic and Applied Ecology* **15**, 336–346.

Bahurmiz, O. M. & Ng, W.-K. (2007). Effects of dietary palm oil source on growth, tissue fatty acid composition and nutrient digestibility of red hybrid tilapia, *Oreochromis sp*., raised from stocking to marketable size. *Aquaculture* **262**, 382–392.

Banabas, M., Turner, M. A., Scotter, D. R. & Nelson, P. N. (2008). Losses of nitrogen fertiliser under oil palm in Papua New Guinea: 1. Water balance, and nitrogen in soil solution and runoff. *Australian Journal of Soil Research* **46**, 332–339.

Barano, T., McKenzie, E., Bhagabati, N., Conte, M., Ennaanay, D., Hadian, O., Olwero, N., Tallis, H., Wolny, S. & Ng, G. (2010). Integrating ecosystem services into spatial planning in Sumatra, Indonesia. TEEBcase see TEEBweb.org.

Barnes, A. D., Jochum, M., Mumme, S., Haneda, N. F., Farajallah, A., Widarto, T. H. & Brose, U. (2014). Consequences of tropical land use for multitrophic biodiversity and ecosystem functioning. *Nature Communications* **5**, 5351.

Barnett, J. B., Benbow, R. L., Ismail, A. & Fellowes, M. D. E. (2013). Abundance and diversity of anurans in a regenerating former oil palm plantation in Selangor, Peninsular Malaysia. *Herpetological Bulletin* **125**, 1–9.

Basiron, Y. (2007). Palm oil production through sustainable plantations. *European Journal of Lipid Science and Technology* **109**, 289–295.

Basri, M., Norman, K. & Hamdan, A. (1995). Natural enemies of the bagworm, *Metisa plana* Walker (Lepidoptera: Psychidae) and their impact on host population regulation. *Crop Protection* **14**, 637–645.

Bateman, I. J., Coombes, E., Fisher, B., Fitzherbert, E., Glew, D. & Niadoo, R. (2009). Saving Sumatra's species: combining economics and ecology to define an efficient and self-sustaining program for inducing conservation within oil palm plantations. CSERGE working paper EDM.

Belcher, B., Rujehan , Imang, N. & Achdiawan, R. (2004). Rattan, rubber, or oil palm: cultural and financial considerations for farmers in Kalimantan. *Economic Botany* **58**, S77–S87.

Bennett, E. & Reynolds, C. (1993). The value of a mangrove area in Sarawak. *Biodiversity and Conservation* **2**, 359–375.

Bhagwat, S. A. & Willis, K. J. (2008). Agroforestry as a solution to the oil-palm debate. *Conservation Biology* **22**, 1368–1369.

Bickel, T., Bruhl, C., Gadau, J., Holldobler, B. & Linsenmair, K. (2006). Influence of habitat fragmentation on the genetic variability in leaf litter ant populations in tropical rainforests of Sabah, Borneo. *Biodiversity and Conservation* **15**, 157–175.

Bilotta, G. S. & Brazier, R. E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research* **42**, 2849–2861.

de Blécourt, M., Hänsel, V. M., Brumme, R., Corre, M. D. & Veldkamp, E. (2014). Soil redistribution by terracing alleviates soil organic carbon losses caused by forest conversion to rubber plantation. *Forest Ecology and Management* **313**, 26–33.

Blitzer, E. J., Dormann, C. F., Holzschuh, A., Klein, A.-M., Rand, T. A. & Tscharntke, T. (2012). Spillover of functionally important organisms between managed and natural habitats. *Agriculture, Ecosystems & Environment* **146**, 34–43.

de Boer, H. J. & Cotingting, C. (2014). Medicinal plants for women's healthcare in southeast Asia: a meta-analysis of their traditional use, chemical constituents, and pharmacology. *Journal of Ethnopharmacology* **151**, 747–767.

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* **320**, 1444–1449.

Borras, S. M. & Franco, J. C. (2012). Global land grabbing and trajectories of agrarian change: a preliminary analysis. *Journal of Agrarian Change* **12**, 34–59.

Bradshaw, C. J. A., Sodhi, N. S., Peh, K. S.-H. & Brook, B. W. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology* **13**, 2379–2395.

Brandi, C., Cabani, T., Hosang, C., Schirmbeck, S., Westermann, L. & Wiese, H. (2012). *Sustainability Standards and Certification – Towards Sustainable Palm Oil in Indonesia?* German Development Institute, Bonn.

Broadbent, E. N., Zambrano, A. M. A., Dirzo, R., Durham, W. H., Driscoll, L., Gallagher, P., Salters, R., Schultz, J., Colmenares, A. & Randolph, S. G. (2012). The effect of land use change and ecotourism on biodiversity: a case study of Manuel Antonio, Costa Rica, from 1985 to 2008. *Landscape Ecology* **27**, 731–744.

Brouwer, L. C. & Riezebos, H. T. (1998). Nutrient dynamics in intact and logged tropical rain forest in Guyana. In *Soils of Tropical Forest Ecosystems* (eds A. Schulte and D. Ruhiyat), pp. 73–86. Springer, Berlin.

Brown, E. & Jacobson, M. F. (2005). *Cruel Oil: How Palm Oil Harms Health, Rainforest, and Wildlife*. Center for Science in the Public Interest, Washington.

Bruijnzeel, L. (2004). Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture Ecosystems & Environment* **104**, 185–228.

Bruun, T. B., de Neergaard, A., Lawrence, D. & Ziegler, A. D. (2009). Environmental consequences of the demise in Swidden cultivation in Southeast Asia: carbon storage and soil quality. *Human Ecology* **37**, 375–388.

Buckle, A., Chia, T., Fenn, M. & Visvalingam, M. (1997). Ranging behaviour and habitat utilisation of the Malayan wood rat (*Rattus tiomanicus*) in an oil palm plantation in Johore, Malaysia. *Crop Protection* **16**, 467–473.

Budidarsono, S., Susanti, A. & Zoomers, E. (2013). Oil palm plantations in Indonesia: the implications for migration, settlement/resettlement and local economic development. In *Biofuels – Economy, Environment and Sustainability* (ed. Z. Fang), pp. 173–193. InTech, Rijeka, Croatia.

Burke, P. J. & Resosudarmo, B. P. (2012). Survey of recent developments. *Bulletin of Indonesian Economic Studies* **48**, 299–324.

Buschman, F. A., Hoitink, A. J. F., de Jong, S. M., Hoekstra, P., Hidayat, H. & Sassi, M. G. (2012). Suspended sediment load in the tidal zone of an Indonesian river. *Hydrology and Earth System Sciences* **16**, 4191–4204.

Campbell-Smith, G., Campbell-Smith, M., Singleton, I. & Linkie, M. (2011). Apes in space: saving an imperilled orangutan population in Sumatra. *PLoS ONE* **6**, e17210.

Campiglia, E., Mancinelli, R., Radicetti, E. & Marinari, S. (2011). Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum annuum* L.) *Nutrient Cycling in Agroecosystems* **89**, 399–412.

Caniago, I. & Siebert, S. F. (1998). Medicinal plant ecology, knowledge and conservation in Kalimantan, Indonesia. *Economic Botany* **52**, 229–250.

Carr, M. (2011). The water relations and irrigation requirements of oil palm (*Elaeis guineensis*): a review. *Experimental Agriculture* **47**, 629–652.

Caudwell, R. W. & Orrell, I. (1997). Integrated pest management for oil palm in Papua New Guinea. *Integrated Pest Management Reviews* **2**, 17–24.

Central Bureau of Statistics Indonesia (2014). Indonesian oil palm statistics 2013.

Chong, K., Zuraini, Z., Sasidharan, S., Devi, P. K., Latha, L. Y. & Ramanathan, S. (2008). Antimicrobial activity of *Elaeis guineensis* leaf. *Pharmacologyonline* **3**, 379–386.

Chung, G. F., Cheah, S. S. & Ramalingam, B. (1999). Effects of pest damage during immature phase on the early yields of oil palm. In *Preprints, 1999 PORIM International Palm Oil Conference*, pp. 454–476. Palm Oil Research Institute Malaysia, Kuala Lumpur.

Chung, A. Y. C., Eggleton, P., Speight, M. R., Hammond, P. M. & Chey, V. K. (2000). The diversity of beetle assemblages in different habitat types in Sabah, Malaysia. *Bulletin of Entomological Research* **90**, 475–496.

CITES (2015). CITES national export quotas for 2015. Available at http://www.cites.org/sites/default/files/common/quotas/2015/ExportQuotas2015.pdf. Accessed July 2015.

Clark, D. B., Clark, D. A., Brown, S., Oberbauer, S. F. & Veldkamp, E. (2002). Stocks and flows of coarse woody debris across a tropical rain forest nutrient and topography gradient. *Forest Ecology and Management* **164**, 237–248.

Cochard, B., Adon, B., Rekima, S., Billotte, N., de Chenon, R. D., Koutou, A., Nouy, B., Omore, A., Purba, A. R., Glazsmann, J.-C. & Noyer, J.-L. (2009). Geographic and genetic structure of African oil palm diversity suggests new approaches to breeding. *Tree Genetics & Genomes* **5**, 493–504.

Cochrane, M. (2003). Fire science for rainforests. *Nature* **421**, 913–919.

Colchester, M. P., Anderson, P., Firdaus, A. Y., Hasibuan, F. & Chao, S. (2011). Human rights abuses and land conflicts in the PT Asiatic Persada concession in Jambi. Report of an independent investigation into land disputes and forest evictions in a palm oil estate. http://www.forestpeoples.org/sites/fpp/files/publication/2011/11/final-report-pt-ap-nov-2011-low-res-1.pdf [Accessed 15.2.2012]

Comte, I., Colin, F., Whalen, J. K., Gruenberger, O. & Caliman, J.-P. (2012). Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review. *Advances in Agronomy* **116**, 71–124.

Corley, R. (2009). How much palm oil do we need? *Environmental Science & Policy* **12**, 134–139.

Corley, R. H. V. & Tinker, P. (eds) (2003). *The Oil Palm*. Fourth Edition (). John Wiley & Sons, Hoboken.

Corre, M. D., Schoorl, J. M., de Koning, F., López-Ulloa, M. & Veldkamp, E. (2015). Erosion and sedimentation effects on soil organic carbon redistribution in a complex landscape of western Ecuador. In *Land-use Change Impacts on Soil Processes in Tropical and Savannah Ecosystems* (eds F. Q. Brearley and A. D. Thomas), pp. 108–121. CAB International, Oxfordshire.

Couwenberg, J., Dommain, R. & Joosten, H. (2010). Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology* **16**, 1715–1732.

Cramb, R. & Curry, G. N. (2012). Oil palm and rural livelihoods in the Asia–Pacific region: an overview. *Asia Pacific Viewpoint* **53**, 223–239.

Danielsen, F., Beukema, H., Burgess, N. D., Parish, F., Bruehl, C. A., Donald, P. F., Murdiyarso, D., Phalan, B., Reijnders, L., Struebig, M. & Fitzherbert, E. B. (2009). Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. *Conservation Biology* **23**, 348–358.

DeBano, L. F. (2000). The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231**, 195–206.

Dechert, G., Veldkamp, E. & Anas, I. (2004). Is soil degradation unrelated to deforestation? Examining soil parameters of land use systems in upland Central Sulawesi, Indonesia. *Plant and Soil* **265**, 197–209.

Dechert, G., Veldkamp, E. & Brumme, R. (2005). Are partial nutrient balances suitable to evaluate nutrient sustainability of land use systems? Results from a case study in Central Sulawesi, Indonesia. *Nutrient Cycling in Agroecosystems* **72**, 201–212.

DeFries, R. S., Morton, D. C., van der Werf, G. R., Giglio, L., Collatz, G. J., Randerson, J. T., Houghton, R. A., Kasibhatla, P. K. & Shimabukuro, Y. (2008). Fire-related carbon emissions from land use transitions in southern Amazonia. *Geophysical Research Letters*, 35, L22705, doi:10.1029/2008GL035689.

Department of Irrigation & Drainage (1989). *Sungai Tekam Experimental Basin Final Report, July 1977 to June 1986*. Malaysian Ministry of Agriculture, Department of Irrigation and Drainage, Kuala Lumpur.

Dhileepan, K. (1994). Variation in populations of the introduced pollinating weevil (*Elaeidobius kamerunicus*) (Coleoptera, Curculionidae) and its impact on fruitset of oil palm (*Elaeis guineensis*) in India. *Bulletin of Entomological Research* **84**, 477–485.

Donald, P. F. (2004). Biodiversity impacts of some agricultural commodity production systems. *Conservation Biology* **18**, 17–37.

Dorren, L. & Rey, F. (2004). A review of the effect of terracing on erosion. In *Briefing Papers of the 2nd SCAPE Workshop*, Cinque Terre, Italy (eds C. Boix-Fayons and A. Imeson), pp. 97–108, SCAPE, Amsterdam.

Dove, M. (2005). Representations of the 'other' by others: the ethnographic challenge posed by planters´ views. In *Transforming the Indonesian Uplands: Marginality Power and Production* (ed. T. Li), pp. 201–228. Taylor & Francis e-library, Amsterdam.

Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y., Faust, H., Fauzi, A. M., Gunawan, D., Hertel, D., Irawan, B., Jaya, I. N. S., Klarner, B., Kleinn, C., Knohl, A., et al. (2016). Ecological and socio-economic functions of tropical lowland rainforest transformation systems: an integrative approach. *Philosophical Transactions of the Royal Society B* **371**, 20150275. doi: 10.1098/rstb.2015.0275

Edinger, E. N., Jompa, J., Limmon, G. V., Widjatmoko, W. & Risk, M. J. (1998). Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. *Marine Pollution Bulletin* **36**, 617–630.

Edwards, F. A., Edwards, D. P., Hamer, K. C. & Davies, R. G. (2013). Impacts of logging and conversion of rainforest to oil palm on the functional diversity of birds in Sundaland. *Ibis* **155**, 313–326.

Edwards, F. A., Edwards, D. P., Larsen, T. H., Hsu, W. W., Benedick, S., Chung, A., Khen, C. V., Wilcove, D. S. & Hamer, K. C. (2014*a*). Does logging and forest conversion to oil palm agriculture alter functional diversity in a biodiversity hotspot? *Animal Conservation* **17**, 163–173.

Edwards, F. A., Edwards, D. P., Sloan, S. & Hamer, K. C. (2014*b*). Sustainable management in crop monocultures: the impact of retaining forest on oil palm yield. *PLoS ONE* **9**, e91695.

Edwards, D. P., Hodgson, J. A., Hamer, K. C., Mitchell, S. L., Ahmad, A. H., Cornell, S. J. & Wilcove, D. S. (2010). Wildlife-friendly oil palm plantations fail to protect biodiversity effectively. *Conservation Letters* **3**, 236–242.

Edwards, D. P., Larsen, T. H., Docherty, T. D. S., Ansell, F. A., Hsu, W. W., Derhe, M. A., Hamer, K. C. & Wilcove, D. S. (2011). Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. *Proceedings of the Royal Society of London Series B* **278**, 82–90.

Ellison, D., Futter, M. N. & Bishop, K. (2012). On the forest cover–water yield debate: from demand-to supply-side thinking. *Global Change Biology* **18**, 806–820.

Emmanuel, N. (2010). Ethno medicines used for treatment of prostatic disease in Foumban, Cameroon. *African Journal of Pharmacy and Pharmacology* **4**, 793–805.

Environment Conservation Department (2002). *Environmental Impact Assessment (EIA) Guidelines on Oil Palm Plantation Development*. Environmental Conservation Department, Kota Kinabalu, Sabah, Malaysia.

Ewing, M. & Msangi, S. (2009). Biofuels production in developing countries: assessing tradeoffs in welfare and food security. *Environmental Science & Policy* **12**, 520–528.

Eyles, A., Beadle, C., Barry, K., Francis, A., Glen, M. & Mohammed, C. (2008). Management of fungal root-rot pathogens in tropical *Acacia mangium* plantations. *Forest Pathology* **38**, 332–355.

Fairhurst, T. H. (1996). *Management of Nutrients for Efficient Use in Small Holder Oil Palm Plantations*. Doctoral Dissertation: Imperial College London (University of London), London.

Famiglietti, J. (2014). The global groundwater crisis. *Nature Climate Change* **4**, 945–948.

FAO (2015). Production/Crops: oil, palm fruit, statistics division. Available at http://faostat3.fao.org/browse/Q/QC/E. Accessed: June 2015.

Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science* **319**, 1235–1238.

Fargione, J. E., Plevin, R. J. & Hill, J. D. (2010). The ecological impact of biofuels. *Annual Review of Ecology, Evolution, and Systematics* **41**, 351–377.

Faruk, A., Belabut, D., Ahmad, N., Knell, R. J. & Garner, T. W. J. (2013). Effects of oil-palm plantations on diversity of tropical anurans. *Conservation Biology* **27**, 615–624.

Fayle, T. M., Turner, E. C., Snaddon, J. L., Chey, V. K., Chung, A. Y. C., Eggleton, P. & Foster, W. A. (2010). Oil palm expansion into rain forest greatly reduces ant biodiversity in canopy, epiphytes and leaf-litter. *Basic and Applied Ecology* **11**, 337–345.

Fearnside, P. M. (1997). Transmigration in Indonesia: lessons from its environmental and social impacts. *Environmental Management* **21**, 553–570.

Fishal, E. M. M., Meon, S. & Yun, W. M. (2010). Induction of tolerance to *Fusarium* wilt and defense-related mechanisms in the plantlets of susceptible Berangan banana pre-inoculated with *Pseudomonas sp* (UPMP3) and *Burkholderia sp* (UPMB3). *Agricultural Sciences in China* **9**, 1140–1149.

Fitzherbert, E. B., Struebig, M. J., Morel, A., Danielsen, F., Bruehl, C. A., Donald, P. F. & Phalan, B. (2008). How will oil palm expansion affect biodiversity? *Trends in Ecology & Evolution* **23**, 538–545.

Foster, W. A., Snaddon, J. L., Turner, E. C., Fayle, T. M., Cockerill, T. D., Ellwood, M. D. F., Broad, G. R., Chung, A. Y. C., Eggleton, P., Khen, C. V. & Yusah, K. M. (2011). Establishing the evidence base for maintaining biodiversity and ecosystem function in the oil palm landscapes of South East Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences* **366**, 3277–3291.

Fowler, D., Nemitz, E., Misztal, P., Di Marco, C., Skiba, U., Ryder, J., Helfter, C., Cape, J. N., Owen, S., Dorsey, J., Gallagher, M. W., Coyle, M., Phillips, G., Davison, B., Langford, B., et al. (2011). Effects of land use on surface-atmosphere exchanges of trace gases and energy in Borneo: comparing fluxes over oil palm plantations and a rainforest. *Philosophical Transactions of the Royal Society, B: Biological Sciences* **366**, 3196–3209.

Frazão, L. A., Paustian, K., Pellegrino Cerri, C. E. & Cerri, C. C. (2013). Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon. *GCB Bioenergy* **5**, 384–390.

Fujinuma, J. & Harrison, R. D. (2012). Wild pigs (*Sus scrofa*) mediate large-scale edge effects in a lowland tropical rainforest in peninsular Malaysia. *PLoS ONE* **7**, e37321.

Gabriel, D. & Tscharntke, T. (2007). Insect pollinated plants benefit from organic farming. *Agriculture, Ecosystems & Environment* **118**, 43–48.

Germer, J. & Sauerborn, J. (2008). Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. *Environment, Development and Sustainability* **10**, 697–716.

Gharibreza, M., Raj, J. K., Yusoff, I., Ashraf, M. A., Othman, Z. & Tahir, W. Z. W. M. (2013). Effects of agricultural projects on nutrient levels in Lake Bera (Tasek Bera), Peninsular Malaysia. *Agriculture Ecosystems & Environment* **165**, 19–27.

Gibson, L., Lee, T. M., Koh, L. P., Brook, B. W., Gardner, T. A., Barlow, J., Peres, C. A., Bradshaw, C. J., Laurance, W. F., Lovejoy, T. E. & Sodhi, N. S. (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* **478**, 378–381.

Gillespie, G. R., Ahmad, E., Elahan, B., Evans, A., Ancrenaz, M., Goossens, B. & Scroggie, M. P. (2012). Conservation of amphibians in Borneo: relative value of secondary tropical forest and non-forest habitats. *Biological Conservation* **152**, 136–144.

Gillison, A. & Liswanti, N. (1999). *Impact of Oil Palm Plantations on Biodiversity in Jambi, Central Sumatra, Indonesia*. Center for International Forestry Research, Bogor.

Gitau, C. W., Gurr, G. M., Dewhurst, C. F., Nicol, H. & Fletcher, M. (2011). Potential for biological control of *Zophiuma butawengi* (Heller) (Hemiptera: Lophopidae) in coconut and oil palms using the hymenopterans *Ooencyrtus sp* (Encyrtidae) and *Parastethynium maxwelli* (Girault) (Mymaridae). *Biological Control* **59**, 187–191.

Glover, D. & Jessup, T. (eds) (2006). *Indonesia's Fires and Haze: The Cost of Catastrophe*. Institute of Southeast Asian Studies and the International Development Research Center. Institute of South East Asian Studies, Singapore.

Goh, K.-J. & Härdter, R. (2003). General oil palm nutrition. In *Oil Palm: Management for Large and Sustainable Yields* (eds T. Fairhurst and R. Härdter), pp. 191–230. PPI/PPIC-IPI, Singapore.
Goh, K.-J., Härdter, R. & Fairhurst, T. (2003). Fertilizing for maximum return. In *Oil Palm Management for Large and Sustainable Yields*, p. 384. PPI, PPIC and IPI, Singapore.
Greathead, D. (1983). The multi-million dollar weevil that pollinates oil palms. *Antenna* **7**, 105–107.
Griffiths, W. & Fairhurst, T. (2003). Implementation of best management practices in an oil palm rehabilitation project. *Better Crops International* **17**, 16.
de Groot, R., Fisher, B., Christie, M., Aronson, J., Braat, L., Haines-Young, R., Gowdy, J., Maltby, E., Neuville, A., Polasky, S., Portela, R. & Ring, I. (2010). Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. In *The Economics of Ecosystems and Biodiversity (TEEB): Ecological and Economic Foundations*, pp. 1–40. Earthscan, London.
de Groot, R., Wilson, M. & Boumans, R. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* **41**, 393–408.
Gruca, M., van Andel, T. R. & Balslev, H. (2014). Ritual uses of palms in traditional medicine in sub-Saharan Africa: a review. *Journal of Ethnobiology and Ethnomedicine* **10**, 60.
Guerrieri, E., Gitau, C. W., Fletcher, M. J., Noyes, J. S., Dewhurst, C. F. & Gurr, G. M. (2011). Description and biological parameters of *Ooencyrtus isabellae* Guerrieri and *Noyes sp nov* (Hymenoptera: Chalcidoidea: Encyrtidae), a potential biocontrol agent of *Zophiuma butawengi* (Heller) (Hemiptera: Fulgoromorpha: Lophopidae) in Papua New Guinea. *Journal of Natural History* **45**, 2747–2755.
Guillaume, T., Damris, M. & Kuzyakov, Y. (2015). Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by δ13C. *Global Change Biology* **21**, 3548–3560.
Haag, D. & Kaupenjohann, M. (2001). Landscape fate of nitrate fluxes and emissions in Central Europe: a critical review of concepts, data, and models for transport and retention. *Agriculture, Ecosystems & Environment* **86**, 1–21.
Hall, D. (2011). Land grabs, land control, and Southeast Asian crop booms. *Journal of Peasant Studies* **38**, 837–857.
Härdter, R., Chow, W. Y. & Hock, O. S. (1997). Intensive plantation cropping, a source of sustainable food and energy production in the tropical rain forest areas in southeast Asia. *Forest Ecology and Management* **91**, 93–102.
Hardwick, S. R., Toumi, R., Pfeifer, M., Turner, E. C., Nilus, R. & Ewers, R. M. (2015). The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: forest disturbance drives changes in microclimate. *Agricultural and Forest Meteorology* **201**, 187–195.
Haron, K., Brookes, P., Anderson, J. & Zakaria, Z. (1998). Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* Jacq) plantations, west Malaysia. *Soil Biology & Biochemistry* **30**, 547–552.
Harsono, S. S., Prochnow, A., Grundmann, P., Hansen, A. & Hallmann, C. (2012). Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia. *Global Change Biology Bioenergy* **4**, 213–228.
Hartemink, A. E. (2005). Plantation agriculture in the tropics: environmental issues. *Outlook on Agriculture* **34**, 11–21.
Hartemink, A. E. (2006). Soil erosion: perennial crop plantations. In *Encyclopedia of Soil Science*, pp. 1613–1617. Taylor & Francis, New York.
Hassler, E., Corre, M. D., Tjoa, A., Damris, M., Utami, S. R. & Veldkamp, E. (2015). Soil fertility controls soil–atmosphere carbon dioxide and methane fluxes in a tropical landscape converted from lowland forest to rubber and oil palm plantations. *Biogeosciences Discussion* **12**, 9163–9207.
Hattori, T., Yamashita, S. & Lee, S.-S. (2012). Diversity and conservation of wood-inhabiting polypores and other aphyllophoraceous fungi in Malaysia. *Biodiversity and Conservation* **21**, 2375–2396.
Hayati, A., Wickneswari, R., Maizura, I. & Rajanaidu, N. (2004). Genetic diversity of oil palm (*Elaeis guineensis* Jacq.) germplasm collections from Africa: implications for improvement and conservation of genetic resources. *Theoretical and Applied Genetics* **108**, 1274–1284.
Hector, A., Fowler, D., Nussbaum, R., Weilenmann, M. & Walsh, R. P. D. (2011). The future of South East Asian rainforests in a changing landscape and climate. *Philosophical Transactions of the Royal Society, B: Biological Sciences* **366**, 3165–3167.
Hedin, L. O., Brookshire, E. J., Menge, D. N. & Barron, A. R. (2009). The nitrogen paradox in tropical forest ecosystems. *Annual Review of Ecology, Evolution, and Systematics* **40**, 613–635.
Henderson, J. & Osborne, D. (2000). The oil palm in all our lives: how this came about. *Endeavour* **24**, 63–68.
Hewitt, C. N., Ashworth, K., Boynard, A., Guenther, A., Langford, B., MacKenzie, A. R., Misztal, P. K., Nemitz, E., Owen, S. M., Possell, M., Pugh, T. A. M., Ryan, A. C. & Wild, O. (2011). Ground-level ozone influenced by circadian control of isoprene emissions. *Nature Geoscience* **4**, 671–674.
Hewitt, C. N., MacKenzie, A. R., Di Carlo, P., Di Marco, C. F., Dorsey, J. R., Evans, M., Fowler, D., Gallagher, M. W., Hopkins, J. R., Jones, C. E., Langford, B., Lee, J. D., Lewis, A. C., Lim, S. F., McQuaid, J., et al. (2009). Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 18447–18451.
Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wosten, H. & Jauhiainen, J. (2010). Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* **7**, 1505–1514.
Hooijer, A., Page, S., Jauhiainen, J., Lee, W. A., Lu, X. X., Idris, A. & Anshari, G. (2012). Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences* **9**, 1053–1071.
Hope, G., Chokkalingam, U. & Anwar, S. (2005). The stratigraphy and fire history of the Kutai Peatlands, Kalimantan, Indonesia. *Quaternary Research* **64**, 407–417.
Huger, A. (2005). The Oryctes virus: its detection, identification, and implementation in biological control of the coconut palm rhinoceros beetle, *Oryctes rhinoceros* (Coleoptera:Scarabaeidae). *Journal of Invertebrate Pathology* **89**, 78–84.
Imaizumi, F., Sidle, R. C. & Kamei, R. (2008). Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. *Earth Surface Processes and Landforms* **33**, 827–840.
IPCC (2007). Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller), 996 pp. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Ishizuka, S., Iswandi, A., Nakajima, Y., Yonemura, S., Sudo, S., Tsuruta, H. & Murdiyarso, D. (2005). The variation of greenhouse gas emissions from soils of various land-use/cover types in Jambi province, Indonesia. *Nutrient Cycling in Agroecosystems* **71**, 17–32.
JabRef Development Team (2015). JabRef. Available at http://jabref.sf.net. accessed January 2014.
Jambari, A., Azhar, B., Ibrahim, N. L., Jamian, S., Hussin, A., Puan, C. L., Noor, H. M., Yusof, E. & Zakaria, M. (2012). Avian biodiversity and conservation in Malaysian oil palm production areas. *Journal of Oil Palm Research* **24**, 1277–1286.
Jauhiainen, J., Silvennoinen, H., Hämäläinen, R., Kusin, K., Limin, S., Raison, R. & Vasander, H. (2012). Nitrous oxide fluxes from tropical peat with different disturbance history and management. *Biogeosciences* **9**, 1337–1350.
Jepson, P. & Ladle, R. J. (2009). Governing bird-keeping in Java and Bali: evidence from a household survey. *Oryx* **43**, 364.
Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., Kinney, P., Bowman, D. M. J. S. & Brauer, M. (2012). Estimated global mortality attributable to smoke from landscape fires. *Environmental Health Perspectives* **120**, 695–701.
Kamphuis, B., Arets, E., Verwer, C., Berg, J., Berkum, S. v. & Harms, B. (2010). *Dutch Trade and Biodiversity: Biodiversity and Socio-economic Impacts of Dutch Trade in Soya, Palm Oil and Timber*. LEI, Wageningen UR, The Hague.
Kemp, P., Sear, D., Collins, A., Naden, P. & Jones, I. (2011). The impacts of fine sediment on riverine fish. *Hydrological Processes* **25**, 1800–1821.
Khalid, A. & Mustafa, W. W. (1992). External benefits of environmental regulation: resource recovery and the utilisation of effluents. *Environmentalist* **12**, 277–285.
Kim, P. S., Jacob, D. J., Mickley, L. J., Koplitz, S. N., Marlier, M. E., DeFries, R. S., Myers, S. S., Chew, B. N. & Mao, Y. H. (2015). Sensitivity of population smoke exposure to fire locations in Equatorial Asia. *Atmospheric Environment* **102**, 11–17.
Klein, A.-M., Vaissiere, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C. & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* **274**, 303–313.
Klinge, R., Martins, A. A., Mackensen, J. & Fölster, H. (2004). Element loss on rain forest conversion in East Amazonia: comparison of balances of stores and fluxes. *Biogeochemistry* **69**, 63–82.
van Klinken, G. (2008). Blood timber and the state in West Kaliamantan, Indonesia. *Asia Pacific Viewpoint* **49**, 35–47.
Koh, L. P. (2008*a*). Birds defend oil palms from herbivorous insects. *Ecological Applications* **18**, 821–825.
Koh, L. P. (2008*b*). Can oil palm plantations be made more hospitable for forest butterflies and birds? *Journal of Applied Ecology* **45**, 1002–1009.
Koh, L. P. (2011). Balancing societies' priorities: an ecologist's perspective on sustainable development. *Basic and Applied Ecology* **12**, 389–393.
Koh, L. P., Levang, P. & Ghazoul, J. (2009). Designer landscapes for sustainable biofuels. *Trends in Ecology & Evolution* **24**, 431–438.
Koh, L. P. & Wilcove, D. S. (2008). Is oil palm agriculture really destroying tropical biodiversity? *Conservation Letters* **1**, 60–64.
de Koning, F., Aguiñaga, M., Bravo, M., Chiu, M., Lascano, M., Lozada, T. & Suarez, L. (2011). Bridging the gap between forest conservation and poverty alleviation: the Ecuadorian Socio Bosque program. *Environmental Science & Policy* **14**, 531–542.
Kosmas, C., Gerontidis, S. & Marathianou, M. (2000). The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece). *Catena* **40**, 51–68.

Kotowska, M. M., Leuschner, C., Triadiati, T., Meriem, S. & Hertel, D. (2015). Quantifying above- and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). *Global Change Biology* **21**, 3620–3634.

Kumar, R. & Okonronkwo, N. (1991). Effectiveness of plant oils against some Bostrychidae infesting cereals in storage. *Insect Science and its Application* **12**, 77–85.

Kurniawan, S. (2016). *Conversion of lowland forests to rubber and oil palm plantations changes nutrient leaching and nutrient retention efficiency in highly weathered soils of Sumatra, Indonesia*. Doctoral Dissertation: University of Göttingen, Göttingen.

Lal, R. (1996). Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. II. Soil chemical properties. *Land Degradation & Development* **7**, 87–98.

Lal, R. (2003). Soil erosion and the global carbon budget. *Environment International* **29**, 437–450.

Lamade, E. & Boillet, J.-P. (2005). Carbon storage and global change: the role of oil palm. *Oleagineux, Corps Gras, Lipides* **12**, 154–160.

Lambin, E. F. & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* **108**, 3465–3472.

Langmann, B., Duncan, B., Textor, C., Trentmann, J. & van der Werf, G. R. (2009). Vegetation fire emissions and their impact on air pollution and climate. *Atmospheric Environment* **43**, 107–116.

Laurance, W. F., Lovejoy, T. E., Vasconcelos, H. L., Bruna, E. M., Didham, R. K., Stouffer, P. C., Gascon, C., Bierregaard, R. O., Laurance, S. G. & Sampaio, E. (2002). Ecosystem decay of Amazonian forest fragments: a 22-year investigation. *Conservation Biology* **16**, 605–618.

Lee, J. S. H., Garcia-Ulloa, J., Ghazoul, J., Obidzinski, K. & Koh, L. P. (2014). Modelling environmental and socio-economic trade-offs associated with land-sparing and land-sharing approaches to oil palm expansion. *Journal of Applied Ecology* **51**, 1366–1377.

Li, T. (2014). The gendered dynamics of Indonesia´s oil palm labour regime. ARI Working Paper 225. Asia Research Institute. National University of Singapore.

Liau, S. S. & Ahmad, A. (1995). Defoliation and crop loss in young oil palm. In *Proceedings of the 1993 PORIM International Palm Oil Congress – Agriculture*, pp. 408–427. Palm Oil Research Institute Malaysia, Kuala Lumpur.

Lim, C. I., Biswas, W. & Samyudia, Y. (2015). Review of existing sustainability assessment methods for Malaysian palm oil production. *Procedia CIRP* **26**, 13–18.

Liow, L., Sodhi, N. & Elmqvist, T. (2001). Bee diversity along a disturbance gradient in tropical lowland forests of south-east Asia. *Journal of Applied Ecology* **38**, 180–192.

Lucey, J. M., Tawatao, N., Senior, M. J. M., Khen, C. V., Benedick, S., Hamer, K. C., Woodcock, P., Newton, R. J., Bottrell, S. H. & Hill, J. K. (2014). Tropical forest fragments contribute to species richness in adjacent oil palm plantations. *Biological Conservation* **169**, 268–276.

Luskin, M. S., Christina, E. D., Kelley, L. C. & Potts, M. D. (2014). Modern hunting practices and wild meat trade in the oil palm plantation-dominated landscapes of Sumatra, Indonesia. *Human Ecology* **42**, 35–45.

Luskin, M. S. & Potts, M. D. (2011). Microclimate and habitat heterogeneity through the oil palm lifecycle. *Basic and Applied Ecology* **12**, 540–551.

Maas, B., Clough, Y. & Tscharntke, T. (2013). Bats and birds increase crop yield in tropical agroforestry landscapes. *Ecology Letters* **16**, 1480–1487.

Macía, M. J. (2004). Multiplicity in palm uses by the Huaorani of Amazonian Ecuador. *Botanical Journal of the Linnean Society* **144**, 149–159.

Mackensen, J., Hölscher, D., Klinge, R. & Fölster, H. (1996). Nutrient transfer to the atmosphere by burning of debris in eastern Amazonia. *Forest Ecology and Management* **86**, 121–128.

Mackie, C. (1984). The lessons behind East Kalimantan's forest fires. *Borneo Research Bulletin* **16**, 63–74.

Maddox, T., Priatna, D., Gemita, E. & Salampessy, A. (2007). *The Conservation of Tigers and Other Wildlife in Oil Palm Plantations: Jambi Province, Sumatra, Indonesia*. Zoological Society of London, London.

Maene, L. M., Thong, K. C., Ong, T. S. & Mokhtaruddin, A. M. (1979). Surface wash under mature oil palm. In *Proceedings, Symposium on Water in Malaysian Agriculture* (ed. E. Pushparajah), pp. 203–216. Malaysian Society of Soil Science, Kuala Lumpur.

Manik, Y., Leahy, J. & Halog, A. (2013). Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia. *International Journal of Life Cycle Assessment* **18**, 1386–1392.

Mantel, S., Wosten, H. & Verhagen, J. (2007). *Biophysical Land Suitability for Oil Palm in Kalimantan, Indonesia*. ISRIC-World Soil Information, Alterra, Plant Research International, Wageningen, UR, Wageningen.

Marlier, M. E., DeFries, R. S., Voulgarakis, A., Kinney, P. L., Randerson, J. T., Shindell, D. T., Chen, Y. & Faluvegi, G. (2013). El Nino and health risks from landscape fire emissions in southeast Asia. *Nature Climate Change* **3**, 131–136.

Mathews, J., Yong, K. K. & Nurulnahar, B. E. (2007). Preliminary investigation on biodiversity and its ecosystem in oil palm plantation. In *International Palm Oil Congress*, pp. 1112–1158. Kuala Lumpur, Malaysia.

Mayfield, M. M. (2005). The importance of nearby forest to known and potential pollinators of oil palm (*Elaeis guineensis* Jacq.; Areceaceae) in southern Costa Rica. *Economic Botany* **59**, 190–196.

McCarthy, J. (2010). Oil palm and agricultural policy: boom or ruin for Indonesian farmers? *East Asia Forum. Economics, Politics and Public Policy in East Asia and the Pacific*, 1–4.

Meijaard, E., Abram, N. K., Wells, J. A., Pellier, A.-S., Ancrenaz, M., Gaveau, D. L. A., Runting, R. K. & Mengersen, K. (2013). People's perceptions about the importance of forests on Borneo. *PLoS ONE* **8**, e73008.

Meijaard, E., Sheil, D., Nasi, R., Augeri, D., Rosenbaum, B., Iskandar, D., Setyawati, T., Lammertink, A., Rachmatika, I., Wong, A., Soehartono, T., Stanley, S. & O'Brien, T. (2005). *Life after Logging: Reconciling Wildlife Conservation and Production Forestry in Indonesian Borneo*. CIFOR, Bogor.

Melling, L., Hatano, R. & Goh, K. (2005*a*). Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. *Soil Biology & Biochemistry* **37**, 1445–1453.

Melling, L., Hatano, R. & Goh, K. (2005*b*). Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. *TELLUS Series B- Chemical and Physical Meteorology* **57**, 1–11.

Melling, L., Hatano, R. & Goh, K. J. (2007). Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia. *Soil Science and Plant Nutrition* **53**, 792–805.

Merten, J., Röll, A., Guillaume, T., Meijide, A., Tarigan, S., Agusta, H., Dislich, C., Dittrich, C., Faust, H., Gunawan, D., Hein, J., Hendrayanto, Knohl, A., Kuzyakov, Y., Wiegand, K. & Hölscher, D. (2016). Water scarcity and oil palm expansion: social views and environmental processes. *Ecology and Society* **21**, 5.

Mesquita, R. C., Delamônica, P. & Laurance, W. F. (1999). Effect of surrounding vegetation on edge-related tree mortality in Amazonian forest fragments. *Biological Conservation* **91**, 129–134.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington.

Misztal, P. K., Nemitz, E., Langford, B., Di Marco, C. F., Phillips, G. J., Hewitt, C. N., MacKenzie, A. R., Owen, S. M., Fowler, D., Heal, M. R. & Cape, J. N. (2011). Direct ecosystem fluxes of volatile organic compounds from oil palms in South-East Asia. *Atmospheric Chemistry and Physics* **11**, 8995–9017.

Moore, S., Evans, C. D., Page, S. E., Garnett, M. H., Jones, T. G., Freeman, C., Hooijer, A., Wiltshire, A. J., Limin, S. H. & Gauci, V. (2013). Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature* **493**, 660–663.

Morton, D., Le Page, Y., DeFries, R., Collatz, G. & Hurtt, G. (2013). Understorey fire frequency and the fate of burned forests in southern Amazonia. *Philosophical Transactions of the Royal Society, B: Biological Sciences* **368**, 20120163.

Mott, J. A., Mannino, D. M., Alverson, C. J., Kiyu, A., Hashim, J., Lee, T., Falter, K. & Redd, S. C. (2005). Cardiorespiratory hospitalizations associated with smoke exposure during the 1997, Southeast Asian forest fires. *International Journal of Hygiene and Environmental Health* **208**, 75–85.

Mumme, S., Jochum, M., Brose, U., Haneda, N. F. & Barnes, A. D. (2015). Functional diversity and stability of litter-invertebrate communities following land-use change in Sumatra, Indonesia. *Biological Conservation* **191**, 750–758.

Muraleedharan, T., Radojevic, M., Waugh, A. & Caruana, A. (2000). Chemical characterisation of the haze in Brunei Darussalam during the 1998 episode. *Atmospheric Environment* **34**, 2725–2731.

Murayama, S. & Bakar, Z. A. (1996). Decomposition of tropical peat soils, 2. Estimation of in situ decomposition by measurement of CO_2 flux. *JARQ Japan Agricultural Research Quarterly* **30**, 153–158.

Murdiyarso, D., Hergoualc'h, K. & Verchot, L. V. (2010). Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 19655–19660.

Murdiyarso, D., Lebel, L., Gintings, A., Tampubolon, S., Heil, A. & Wasson, M. (2004). Policy responses to complex environmental problems: insights from a science–policy activity on transboundary haze from vegetation fires in Southeast Asia. *Agriculture, Ecosystems & Environment* **104**, 47–56.

Murdiyarso, D., Noordwijk, M. V., Wasrin, U. R., Tomich, T. P. & Gillison, A. (2002). Environmental benefits and sustainable land-use options in the Jambi transect, Sumatra. *Journal of Vegetation Science* **13**, 429–438.

Murphy, D. J. (2007). Future prospects for oil palm in the 21st century: biological and related challenges. *European Journal of Lipid Science and Technology* **109**, 296–306.

Murtilaksono, K., Darmosarkoro, W., Sutarta, E. S., Siregar, H. H., Hidayat, Y. & Yusuf, M. A. (2011). Feasibility of soil and water conservation techniques on oil palm plantation. *Agrivita* **33**, 63.

Nagoya Protocol (2011). *Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity*. Secretariat of the Convention on Biological Diversity, Montreal.

Naidoo, R., Malcolm, T. & Tomasek, A. (2009). Economic benefits of standing forests in highland areas of Borneo: quantification and policy impacts. *Conservation Letters* **2**, 35–44.

Nair, K. (2001). *Pest Outbreaks in Tropical Forest Plantations: Is There a Greater Risk for Exotic Tree Species?* Center for International Forestry Research, Bogor.

Nash, S. V. (1993). *Sold for a Song: The Trade in Southeast Asian Non-CITES Birds. TRAFFIC Network Report*. TRAFFIC International, Cambridge.

Nesadurai, H. E. S. (2013). Food security, the palm oil-land conflict nexus, and sustainability: a governance role for a private multi-stakeholder regime like the RSPO? *Pacific Review* **26**, 505–529.

New, T. (2005). 'Inordinate fondness': a threat to beetles in south east Asia? *Journal of Insect Conservation* **9**, 147–150.

Ng, P. K. & Tan, H. (1997). Freshwater fishes of Southeast Asia: potential for the aquarium fish trade and conservation issues. *Aquarium Sciences and Conservation* **1**, 79–90.

Ngoze, S., Riha, S., Lehmann, J., Verchot, L., Kinyangi, J., Mbugua, D. & Pell, A. (2008). Nutrient constraints to tropical agroecosystem productivity in long-term degrading soils. *Global Change Biology* **14**, 2810–2822.

Nijman, V. (2010). An overview of international wildlife trade from Southeast Asia. *Biodiversity and Conservation* **19**, 1101–1114.

van Noordwijk, M., Mulyoutami, E., Sakuntaladewi, N. & Agus, F. (2008). *Swiddens in Transition: Shifted Perceptions on Shifting Cultivators in Indonesia*. World Agroforestry Centre, Bogor.

Nooteboom, G. & de Jong, E. B. P. (2010). Against 'green development fantasies': resource degradation and the lack of community resistance in the Middle Mahakam Wetlands, East Kalimantan, Indonesia. *Asian Journal of Social Science* **38**, 258–278.

Norhayati, A., Ehwan, N. & Okuda, T. (2014). Assessment of riparian ecosystem on amphibians along a green corridor in oil palm plantation, Pasoh, Negeri Sembilan, Peninsular Malaysia. *Sains Malaysiana* **43**, 655–666.

Norris, K., Asase, A., Collen, B., Gockowksi, J., Mason, J., Phalan, B. & Wade, A. (2010). Biodiversity in a forest-agriculture mosaic – The changing face of West African rainforests. *Biological Conservation* **143**, 2341–2350.

Norris, R. F., Caswell-Chen, E. P. & Kogan, M. (2003). *Concepts in Integrated Pest Management*. Prentice Hall, Upper Saddle River.

Obidzinski, K., Andriani, R., Komanidin, H. & Andrianto, A. (2012). Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecology and Society* **17**, 25.

Oerke, E. C. (2006). Crop losses to pests. *Journal of Agricultural Science* **144**, 31–43.

Okwute, L. O. & Isu, N. R. (2007). The environmental impact of palm oil mill effluent (POME) on some physico-chemical parameters and total aerobic bioload of soil at a dump site in Anyigba, Kogi State, Nigeria. *African Journal of Agricultural Research* **2**, 656–662.

Ollerton, J., Winfree, R. & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos* **120**, 321–326.

O'Loughlin, C. L. (1984). Effectiveness of introduced forest vegetation for protection against landslides and erosion in New Zealand's steeplands. In *Symposium on Effects of Forest Land Use on Erosion and Slope Stability*, pp. 275–280. University of Hawaii, Honolulu, Hawaii.

Opute, F. I. (1975). Lipid and sterol composition of the pollen of the west African oilpalm, *Elaeis guineensis*. *Phytochemistry* **14**, 1023–1026.

Ostermann, K. & Brauer, M. (2001). Air quality during haze episodes and its impact on health. In *Forest Fires and Regional Haze in Southeast Asia* (eds P. Eaton, M. Radojevic and E. Peter), pp. 41–66. Nova Science Publishers, Huntington.

Othman, H., Mohammed, A. T., Darus, F. M., Harun, M. H. & Zambri, M. P. (2011). Best management practices for oil palm cultivation on peat: ground water-table maintenance in relation to peat subsidence and estimation of CO_2 emissions at Sessang, Sarawak. *Journal of Oil Palm Research* **23**, 1078–1086.

Page, S., Hoscilo, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L., Vasander, H. & Limin, S. (2009). Restoration ecology of lowland tropical peatlands in Southeast Asia: current knowledge and future research directions. *Ecosystems* **12**, 888–905.

Page, S. E., Morrison, R., Malins, C., Hooijer, A., Rieley, J. O. & Jauhiainen, J. (2011*a*). *Review of Peat Surface Greenhouse Gas Emissions from Oil Palm Plantations in Southeast Asia* ICCT White Paper 15, International Council on Clean Transportation (ICCT), Washington DC.

Page, S. E., Rieley, J. O. & Banks, C. J. (2011*b*). Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* **17**, 798–818.

Page, S. E., Siegert, F., Rieley, J. O., Boehm, H.-D. V., Jaya, A. & Limin, S. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420**, 61–65.

Palm, C. & Sanchez, P. (1990). Decomposition and nutrient release patterns of the leaves of three tropical legumes. *Biotropica* **22**, 330–338.

Pan, Y., Birdsey, R. A., Phillips, O. L. & Jackson, R. B. (2013). The structure, distribution, and biomass of the world's forests. *Annual Review of Ecology, Evolution, and Systematics* **44**, 593–622.

Paoli, G. D., Yaap, B., Wells, P. L. & Sileuw, A. (2010). CSR, oil palm and the RSPO: translating boardroom philosophy into conservation action on the ground. *Tropical Conservation Science* **3**, 438–446.

Pennock, D. & Corre, M. (2001). Development and application of landform segmentation procedures. *Soil and Tillage Research* **58**, 151–162.

Peshin, R. & Pimentel, D. (eds) (2014). *Integrated Pest Management*. Springer Netherlands, Dordrecht.

Pfund, J.-L., Watts, J. D., Boissière, M., Boucard, A., Bullock, R. M., Ekadinata, A., Dewi, S., Feintrenie, L., Levang, P., Rantala, S., Sheil, D., Sunderland, T. C. H. & Urech, Z. L. (2011). Understanding and integrating local perceptions of trees and forests into incentives for sustainable landscape management. *Environmental Management* **48**, 334–349.

Phelps, J. & Webb, E. L. (2015). 'Invisible' wildlife trades: Southeast Asia's undocumented illegal trade in wild ornamental plants. *Biological Conservation* **186**, 296–305.

Poku, K. (2002). Small-scale palm oil processing in Africa. *FAO Agricultural Services Bulletin* **148**, 1–60.

Ponnamma, K. N. (2001). Biological control of pests of oil palm. In *Biocontrol Potential and its Exploitation in Sustainable Agriculture, Volume 2: Insect Pests* (eds R. K. Upadhyay, K. G. Mukerji and B. P. Chamola), pp. 235–260. Springer US, Boston.

Posa, M. R. C., Wijedasa, L. S. & Corlett, R. T. (2011). Biodiversity and conservation of tropical peat swamp forests. *BioScience* **61**, 49–57.

Potineni, K. & Saravanan, L. (2013). Natural enemies of oil palm defoliators and their impact on pest population. *Pest Management in Horticultural Ecosystems* **19**, 179–184.

Potter, L. (2009). Oil palm and resistance in West Kalimantan, Indonesia. In *Agrarian Angst and Rural Resistance in Contemporary Southeast Asia* (eds D. Caouette and S. Turner), pp. 105–134. Routledge, London.

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O. & Kunin, W. E. (2010). Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution* **25**, 345–353.

Prescott, G. W., Edwards, D. P. & Foster, W. A. (2015). Retaining biodiversity in intensive farmland: epiphyte removal in oil palm plantations does not affect yield. *Ecology and Evolution* **5**, 1944–1954.

Priwiratama, H. & Susanto, A. (2014). Utilization of fungi for the biological control of insect pests and *Ganoderma* disease in the Indonesian oil palm industry. *Journal of Agricultural Science and Technology* **4**, 103–111.

Pyle, J. A., Warwick, N. J., Harris, N. R. P., Abas, M. R., Archibald, A. T., Ashfold, M. J., Ashworth, K., Barkley, M. P., Carver, G. D., Chance, K., Dorsey, J. R., Fowler, D., Gonzi, S., Gostlow, B., Hewitt, C. N., et al. (2011). The impact of local surface changes in Borneo on atmospheric composition at wider spatial scales: coastal processes, land-use change and air quality. *Philosophical Transactions of the Royal Society B: Biological Sciences* **366**, 3210–3224.

Rajavel, V., Abdul Sattar, M. Z., Abdulla, M. A., Kassim, N. M. & Abdullah, N. A. (2012). Chronic administration of oil palm (*Elaeis guineensis*) leaves extract attenuates hyperglycaemic-induced oxidative stress and improves renal histopathology and function in experimental diabetes. *Evidence-Based Complementary and Alternative Medicine* 2012, 12, doi:10.1155/2012/195367.

Ramsay, W. J. H. (1987*a*). Deforestation and erosion in the Nepalese Himalaya: is the link myth or reality. *International Association of Scientific Hydrology* **167**, 239–250.

Ramsay, W. J. H. (1987*b*). Sediment production and transport in the Phewa valley, Nepal. *International Association of Scientific Hydrology* **165**, 461–472.

Ratnasingam, J., Vacalie, C., Sestras, A. F. & Ioras, F. (2014). Public perception of forestry practices in Malaysia. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **42**, 280–285.

Reddington, C. L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y. Y., Arnold, S. R. & Spracklen, D. V. (2014). Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia. *Environmental Research Letters* **9**, 094006.

Reijnders, L. & Huijbregts, M. A. J. (2008). Palm oil and the emission of carbon-based greenhouse gases. *Journal of Cleaner Production* **16**, 477–482.

Rieley, J. O. (2007). Tropical peatland – The amazing dual ecosystem: coexistence and mutual benefit. In *Proceedings of the International Symposium and Workshop on Tropical Peatland*, pp. 1–14. EU CARBOPEAT and RESTORPEAT Partnership, Gadjah Mada University, Indonesia and University of Leicester, Leicester, UK, Yogyakarta.

Rieley, J. O. & Page, S. (1997). Biodiversity and sustainability of tropical peatlands. *Proceedings of the International Symposium on Biodiversity, Environmental Importance and Sustainability of Tropical Peat and Peatlands*, Palangka Raya, Central Kalimantan, 4–8 September 1995. 370 pp. Samara Publishing Ltd., Cardigan, UK.

Rist, L., Feintrenie, L. & Levang, P. (2010). The livelihood impacts of oil palm: smallholders in Indonesia. *Biodiversity and Conservation* **19**, 1009–1024.

Rodríguez, J. P., Beard, T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J., Dobson, A. P. & Peterson, G. D. (2006). Trade-offs across space, time, and ecosystem services. *Ecology and Society* **11**, 28.

Royal Society (2008). *Science Policy Report 15/08. Ground-level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications*. The Royal Society, London.

Sakata, R., Shimada, S., Arai, H., Yoshioka, N., Yoshioka, R., Aoki, H., Kimoto, N., Sakamoto, A., Melling, L. & Inubushi, K. (2015). Effect of soil types and nitrogen fertilizer on nitrous oxide and carbon dioxide emissions in oil palm plantations. *Soil Science and Plant Nutrition* **61**, 48–60.

Sarada, S., Nair, G. S. & Reghunath, B. (2002). Quantification of medicinally valuable weeds in oil palm plantations of Kerala. *Journal of Tropical Agriculture* **40**, 19–26.

Sasidharan, S., Logeswaran, S. & Latha, L. Y. (2012). Wound healing activity of *Elaeis guineensis* leaf extract ointment. *International Journal of Molecular Sciences* **13**, 336–347.

Sasidharan, S., Nilawatyi, R., Xavier, R., Latha, L. Y. & Amala, R. (2010). Wound healing potential of *Elaeis guineensis* Jacq leaves in an infected albino rat model. *Molecules* **15**, 3186–3199.

Savilaakso, S., Garcia, C., Garcia-Ulloa, J., Ghazoul, J., Groom, M., Guariguata, M. R., Laumonier, Y., Nasi, R., Petrokofsky, G., Snaddon, J. & Zrust, M. (2014). Systematic review of effects on biodiversity from oil palm production. *Environmental Evidence* **3**, 1–21.

Schippmann, U., Leaman, D. J. & Cunningham, A. B. (2002). Impact of cultivation and gathering of medicinal plants on biodiversity: global trends and issues. pp 142–167 in *Biodiversity and the Ecosystem Approach in Agriculture, Forestry and Fisheries*. Food and Agriculture Organization, Rome.

Schoorl, J., Sonneveld, M. & Veldkamp, A. (2000). Three-dimensional landscape process modelling: the effect of DEM resolution. *Earth Surface Processes and Landforms* **25**, 1025–1034.

Schoorl, J. & Veldkamp, A. (2001). Linking land use and landscape process modelling: a case study for the Alora region (south Spain). *Agriculture, Ecosystems & Environment* **85**, 281–292.

Schoorl, J., Veldkamp, A. & Bouma, J. (2002). Modeling water and soil redistribution in a dynamic landscape context. *Soil Science Society of America Journal* **66**, 1610–1619.

Schrier-Uijl, A. P., Silvius, M., Parish, F., Lim, K. H., Rosediana, S. & Anshari, G. (2013). *Environmental and Social Impacts of Oil Palm Cultivation on Tropical Peat – A Scientific Review*. Roundtable on Sustainable Oil Palm, Kuala Lumpur.

Senior, M. J. M., Hamer, K. C., Bottrell, S., Edwards, D. P., Fayle, T. M., Lucey, J. M., Mayhew, P. J., Newton, R., Peh, K. S. H., Sheldon, F. H., Stewart, C., Styring, A. R., Thom, M. D. F., Woodcock, P. & Hill, J. K. (2013). Trait-dependent declines of species following conversion of rain forest to oil palm plantations. *Biodiversity and Conservation* **22**, 253–268.

Shackleton, S., Delang, C. O. & Angelsen, A. (2011). From subsistence to safety nets and cash income: exploring the diverse values of non-timber forest products for livelihoods and poverty alleviation. In *Non-timber Forest Products in the Global Context* (eds S. Shackleton, C. Shackleton and P. Shanley), pp. 55–81. Springer, London.

Shafie, N. J., Sah, S. A. M., Latip, N. S. A., Azman, N. M. & Khairuddin, N. L. (2011). Diversity pattern of bats at two contrasting habitat types along Kerian River, Perak, Malaysia. *Tropical Life Sciences Research* **22**, 13.

Sheil, D., Casson, A., Meijaard, E., van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K. & Kanninen, M. (2009). *The Impacts and Opportunities of Oil Palm in Southeast Asia: What do We Know and What do We Need to Know*. CIFOR, Bogor.

Sheil, D. & Liswanti, N. (2006). Scoring the importance of tropical forest landscapes with local people: patterns and insights. *Enivornmental Management* **38**, 126–136.

Sheil, D., Puri, R., Wan, M., Basuki, I., van Heist, M., Liswanti, N., Rachmatika, I. & Samsoedin, I. (2006). Recognizing local people's priorities for tropical forest biodiversity. *AMBIO: A Journal of the Human Environment* **35**, 17–24.

Shine, R., Ambariyanto , Harlow, P. S. & Mumpuni (1999). Ecological attributes of two commercially-harvested Python species in northern Sumatra. *Journal of Herpetology* **33**, 249–257.

Siddiqui, Y., Meon, S., Ismail, M. R. & Ali, A. (2008). Trichoderma-fortified compost extracts for the control of choanephora wet rot in okra production. *Crop Protection* **27**, 385–390.

Sidle, R. C., Ziegler, A. D., Negishi, J. N., Nik, A. R., Siew, R. & Turkelboom, F. (2006). Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management* **224**, 199–225.

Silvius, M., Oneka, M. & Verhagen, A. (2000). Wetlands: lifeline for people at the edge. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **25**, 645–652.

Smith, D. R., Townsend, T. J., Choy, A. W. K., Hardy, I. C. W. & Sjoegersten, S. (2012). Short-term soil carbon sink potential of oil palm plantations. *Global Change Biology Bioenergy* **4**, 588–596.

Sodhi, N. S., Koh, L. P., Brook, B. W. & Ng, P. K. (2004). Southeast Asian biodiversity: an impending disaster. *Trends in Ecology & Evolution* **19**, 654–660.

Sodhi, N. S., Koh, L. P., Clements, R., Wanger, T. C., Hill, J. K., Hamer, K. C., Clough, Y., Tscharntke, T., Posa, M. R. C. & Lee, T. M. (2010). Conserving Southeast Asian forest biodiversity in human-modified landscapes. *Biological Conservation* **143**, 2375–2384.

Sommer, R., Denich, M. & Vlek, P. L. (2000). Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. *Plant and Soil* **219**, 231–241.

Starkel, L. (1972). The role of catastrophic rainfall in the shaping of the relief of the Lower Himalaya (Darjeeling Hills). *Geographia Polonia* **21**, 103–147.

Steinebach, S. (2013). 'Today we occupy the plantation, tomorrow Jakarta.' Indigeneity, land and oil palm plantations in Jambi. In *Adat and Indigeneity in Indonesia. Culture and Entitlements between Heterogeneity and Selfascription* (ed. B. Hauser-Schäublin), pp. 63–81. Universitätsverlag Göttingen, Göttingen.

Stichnothe, H. & Schuchardt, F. (2010). Comparison of different treatment options for palm oil production waste on a life cycle basis. *The International Journal of Life Cycle Assessment* **15**, 907–915.

van Straaten, O., Corre, M. D., Wolf, K., Tchienkoua, M., Cuellar, E., Matthews, R. & Veldkamp, E. (2015). Conversion of lowland tropical forests to tree cash-crop plantations loses up to one-half of stored soil organic carbon. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 9956–9960.

Struebig, M. J., Kingston, T., Petit, E. J., Le Comber, S. C., Zubaid, A., Mohd-Adnan, A. & Rossiter, S. J. (2011). Parallel declines in species and genetic diversity in tropical forest fragments. *Ecology Letters* **14**, 582–590.

Suhaily, S., Jawaid, M., Khalil, H. P. S. A., Mohamed, A. & Ibrahim, F. (2012). A review of oil palm biocomposites for furniture design and applications: potential and challenges. *BioResources* **7**, 4400–4423.

Sundram, S., Abdullah, F., Ahmad, Z. A. M. & Yusuf, U. K. (2008). Efficacy of single and mixed treatments of *Trichoderma harzianum* as biocontrol agents of Ganoderma basal stem rot of oil palm. *Journal of Oil Palm Research* **20**, 470–483.

Sundram, S., Meon, S., Abu Seman, I. & Othman, R. (2011). Symbiotic interaction of endophytic bacteria with arbuscular mycorrhizal fungi and its antagonistic effect on Ganoderma boninense. *Journal of Microbiology* **49**, 551–557.

Suryanto, D., Wibowo, R. H., Siregar, E. B. M. & Munir, E. (2012). A possibility of chitinolytic bacteria utilization to control basal stems disease caused by *Ganoderma boninense* in oil palm seedling. *African Journal of Microbiology Research* **6**, 2053–2059.

Susanto, A., Sudharto, P. & Purba, R. (2005). Enhancing biological control of basal stem rot disease (*Ganoderma boninense*) in oil palm plantations. *Mycopathologia* **159**, 153–157.

Swanson, F. J., Kratz, T. K., Caine, N. & Woodmansee, R. G. (1988). Landform effects on ecosystem patterns and processes. *BioScience* **38**, 92–98.

Tan, K. T., Lee, K. T., Mohamed, A. R. & Bhatia, S. (2009). Palm oil: addressing issues and towards sustainable development. *Renewable and Sustainable Energy Reviews* **13**, 420–427.

Tanaka, S., Tachibe, S., Wasli, M. E. B., Lat, J., Seman, L., Kendawang, J. J., Iwasaki, K. & Sakurai, K. (2009). Soil characteristics under cash crop farming in upland areas of Sarawak, Malaysia. *Agriculture Ecosystems & Environment* **129**, 293–301.

Teuscher, M., Vorlaufer, M., Wollni, M., Brose, U., Mulyani, Y. & Clough, Y. (2015). Trade-offs between bird diversity and abundance, yields and revenue in smallholder oil palm plantations in Sumatra, Indonesia. *Biological Conservation* **186**, 306–318.

Therville, C., Feintrenie, L. & Levang, P. (2011). Farmers' perspectives about agroforests conversion to plantations in Sumatra. Lessons learnt from Bungo district (Jambi, Indonesia). *Forests, Trees and Livelihoods* **20**, 15–33.

Thomas, R. L., Watson, I. & Hardon, J. J. (1969). Inheritance of some components of yield in the 'deli dura variety' of oil palm. *Euphytica* **18**, 92–100.

Tomich, T. P., de Foresta, H., Dennis, R., Ketterings, Q., Murdiyarso, D., Palm, C., Stolle, F., Suyanto, S. & van Noordwijk, M. (2002). Carbon offsets for conservation and development in Indonesia? *American Journal of Alternative Agriculture* **17**, 125–137.

Tscharntke, T., Bommarco, R., Clough, Y., Crist, T. O., Kleijn, D., Rand, T. A., Tylianakis, J. M., van Nouhuys, S. & Vidal, S. (2007). Conservation biological control and enemy diversity on a landscape scale. *Biological Control* **43**, 294–309.

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. & Whitbread, A. (2012*a*). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* **151**, 53–59.

Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T. O., Dormann, C. F., Ewers, R. M., Fründ, J., Holt, R. D., Holzshuch, A., Klein, A. M., et al. (2012*b*). Landscape moderation of biodiversity patterns and processes-eight hypotheses. *Biological Reviews* **87**, 661–685.

USDA FAS (2012). Malaysia: stagnating palm oil yields impede growth. United States Department of Agriculture Foreign Agricultural Service.

Vakili, M., Rafatullah, M., Ibrahim, M. H., Abdullah, A. Z., Salamatinia, B. & Gholami, Z. (2014). Oil palm biomass as an adsorbent for heavy metals. *Reviews of Environmental Contamination and Toxicology* **232**, 61–88.

Vaknin, Y. (2012). The significance of pollination services for biodiesel feedstocks, with special reference to *Jatropha curcas* L.: a review. *Bioenergy Research* **5**, 32–40.

Vellend, M. (2003). Island biogeography of genes and species. *The American Naturalist* **162**, 358–365.

Vermeulen, S. & Goad, N. (2006). *Towards Better Practice in Smallholder Palm Oil Production*. International Institute for Environment and Development, London.

Wahid, M. B., Abdullah, S. N. A. & Henson, I. (2005). Oil palm-achievements and potential. *Plant Production Science* **8**, 288–297.

Walsh, R. P. D., Nussbaum, R., Fowler, D., Weilenmann, M. & Hector, A. (2011). Conclusion: applying South East Asia Rainforest Research Programme science to land-use management policy and practice in a changing landscape and climate. *Philosophical Transactions of the Royal Society B: Biological Sciences* **366**, 3354–3358.

Wanrosli, W., Zainuddin, Z., Law, K. & Asro, R. (2007). Pulp from oil palm fronds by chemical processes. *Industrial Crops and Products* **25**, 89–94.

Watkins, C. (2015). African oil palms, colonial socioecological transformation and the making of an Afro-Brazilian landscape in Bahia, Brazil. *Environment and History* **21**, 13–42.

Whitten, A. J., Damanik, S. J., Anwar, J. & Hisyam, N. (1984). *The Ecology of Sumatra*. Periplus Editions (HK) Ltd., Singapore.

Wicke, B., Dornburg, V., Junginger, M. & Faaij, A. (2008). Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass & Bioenergy* **32**, 1322–1337.

Wilkinson, M. J., Owen, S. M., Possell, M., Hartwell, J., Gould, P., Hall, A., Vickers, C. & Hewitt, C. N. (2006). Circadian control of isoprene emissions from oil palm (*Elaeis guineensis*). *Plant Journal* **47**, 960–968.

Wood, B. J. (2002). Pest control in Malaysia's perennial crops: a half century perspective tracking the pathway to integrated pest management. *Integrated Pest Management Reviews* **7**, 173–190.

Wood, B. & Fee, C. (2003). A critical review of the development of rat control in Malaysian agriculture since the 1960s. *Crop Protection* **22**, 445–461.

Woruba, D. N., Priest, M. J., Dewhurst, C. F., Gitau, C. W., Fletcher, M. J., Nicol, H. I. & Gurr, G. M. (2014). Entomopathogenic fungi of the oil palm pest, *Zophiuma butawengi* (Fulgoromorpha: Lophopidae), and potential for use as biological control agents. *Austral Entomology* **53**, 268–274.

Wösten, J., Ismail, A. & Van Wijk, A. (1997). Peat subsidence and its practical implications: a case study in Malaysia. *Geoderma* **78**, 25–36.

Yaap, B., Struebig, M. J., Paoli, G. & Koh, L. P. (2010). Mitigating the biodiversity impacts of oil palm development. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **5**, 1–11.

Yacob, S., Hassan, M. A., Shirai, Y., Wakisaka, M. & Subash, S. (2006). Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment. *Science of the Total Environment* **366**, 187–196.

Yule, C. M. (2010). Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests. *Biodiversity and Conservation* **19**, 393–409.

Yusoff, S. (2006). Renewable energy from palm oil – innovation on effective utilization of waste. *Journal of Cleaner Production* **14**, 87–93.

Yusoff, S. & Hansen, S. (2007). Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia (9 pp). *The International Journal of Life Cycle Assessment* **12**, 50–58.

Yusop, Z., Chan, C. H. & Katimon, A. (2007). Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment. *Water Science and Technology* **56**, 41–48.

Zimmer, Y. (2010). Competitiveness of rapeseed, soybeans and palm oil. *Journal of Oilseed Brassica* **1**, 84–90.

Zoological Society London (2015). Sustainable palm oil platform. Zoological Society London. Available at: http://www.sustainablepalmoil.org/growers-millers/growers/smallholders/ Accessed 25.7.2015.

Zurita, G., Pe'er, G., Bellocq, M. I. & Hansbauer, M. M. (2012). Edge effects and their influence on habitat suitability calculations: a continuous approach applied to birds of the Atlantic forest. *Journal of Applied Ecology* **49**, 503–512.

VIII. SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Appendix S1. Oil palm expansion over time.

Appendix S2. Literature search terms.

Appendix S3. JabRef database.

Appendix S4. Rationale for net ecosystem function effects.

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