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TOPICAL REVIEW

Systematic mapping shows the need for increased socio-ecological research on oil palm

Valentine Joy Reiss-Woolever[1], **Sarah Helen Luke**[1], **Jake Stone**[1], **Gorm Eirik Shackelford**[2,3] and **Edgar Clive Turner**[1]

[1] Insect Ecology Group, Department of Zoology, University of Cambridge, Cambridge, United Kingdom
[2] Conservation Science Group, Department of Zoology, University of Cambridge, Cambridge, United Kingdom
[3] BioRISC (Biosecurity Research Initiative at St. Catharine's), St. Catharine's College, Cambridge, United Kingdom

E-mail: vjr30@cam.ac.uk

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Abstract
In the past century, oil palm has developed from a sustenance crop in West Africa to a major global agricultural commodity, with substantial impacts on biodiversity, the environment, society, and livelihoods. Although the oil palm industry contributes to local and national economies across the tropics, there are significant concerns about the negative effects of oil palm cultivation on biodiversity and ecosystem functioning, as well on local communities and farmers. There is a growing awareness of the need for managing agricultural landscapes more sustainably, and the importance of ecological, social, and also interdisciplinary research to inform this. To understand the current status of research across these areas for oil palm, we carried out a systematic mapping exercise to quantify social, ecological, and interdisciplinary socio-ecological research on oil palm cultivation, assess trends in the research, and to identify priority knowledge gaps in the literature. Literature was searched using adapted preferred reporting items for systematic reviews and meta-analyses and Collaboration for Environmental Evidence protocols. We reviewed 4959 publications on the ecological, social, and socioecological effects of oil palm cultivation. Each publication was classified according to study context (the study site location and type), comparators (the type of comparison the study makes), intervention (the potential action or decision being studied), and outcome (the effects of the intervention on the population). This resulted in 443 classified papers, which we then analyzed in more detail, to identify co-occurrence of different research foci between the disciplines and in socio-ecological research. We found a global increase in oil palm research over the past three decades, with a clear bias to Malaysia and Indonesia, mirroring global production trends. Over 70% of the research was focused on ecological outcomes, 19% on social, and less than 10% interdisciplinary. The majority of studies were conducted within industrial plantations, with comparisons to non-modified habitats, such as forests. Research has focused most on the effects of cultivation on yield, invertebrate biodiversity, and livelihood. To place our findings in context of production of palm oil and sustainability priorities, we used information on regional oil palm production in Tonnes, priorities of sustainable certification bodies, and recognized causes of yield gaps. The most pressing knowledge gaps included a lack of studies on the effects of plantation inputs on pollination and herbivory, the relationship between ecological factors and human health and wellbeing, and comparisons of different management practices within oil palm plantations. We advocate that these gaps become the focus of future research attention, as they lie in identified priority research areas and outcomes are likely to be critical to informing the development of more sustainable palm oil production.

1. Introduction

Environmental change due to agricultural demand has transformed landscapes worldwide, causing widespread loss of natural habitats and biodiversity (Sala *et al* 2000). While increased agricultural production is necessary to feed a growing global population and support the livelihoods of 30% of the population (FAO 2019), cultivation can have severe negative effects on the environment. A notable example of this is seen in the palm oil industry. Oil palm (*Elaeis guineensis)* is one of the most rapidly expanding crops in the tropics (Vijay *et al* 2016). Under optimal efficiency, oil palm is capable of 5–9 times higher yield per area than other oilseed crops and is responsible for 40% of global vegetable oil used in food, cosmetics and biofuels (Prokurat 2013). This, alongside the potential 20–30 year economic lifespan of plantations, has made oil palm one of the most lucrative crops in the tropics (Sayer *et al* 2012). Global production has doubled between 2003 and 2013 in countries across South America, Africa, and Asia (RSPO 2018). In these regions this expansion of oil palm has largely been at the expense of tropical forests, which support two-thirds of the world's floral and faunal diversity and store a quarter of terrestrial carbon (Bonan 2008).

As tropical land devoted to oil palm has increased, so has the attention the industry has received from the scientific community (Savilaakso *et al* 2014). The conversion of forests to oil palm plantations and resulting reduction in environmental heterogeneity and habitat complexity has been a frequent focus of ecological research (Dislich *et al* 2015). Land transformations have many negative consequences for animal communities and the ecosystem functions they support, including reduced carbon sequestration, pollination, and soil fertility (Barnes *et al* 2014). Studies comparing oil palm to tropical forest have found a 35% reduction in species richness (Dhandapani 2015) and negative effect on over 75% of key ecosystem services (Dislich *et al* 2015) after conversion. However, oil palm cultivation can also bring a wide range of benefits for human livelihoods, and has much higher land-use efficiency compared to many other alternative crops (de Vries *et al* 2010). A growing number of rural communities work on these plantations, with the oil palm industry providing employment for over 4.5 million farmers in Southeast Asia alone (Vermeulen *et al* 2006). Sociologists have noted the impacts of cultivation on livelihoods (Krishna *et al* 2015), household dynamics (Hasanah *et al* 2019), and farmer satisfaction (Feintrenie *et al* 2010), with some studies highlighting the positive impact both large and small-scale cultivation has provided to rural and national economies (Dürr 2017). However, negative impacts have also been recorded on social themes such as gender inequality (Levien 2017), and rights of indigenous people (Colchester *et al* 2006). In both ecological and social disciplines, it is clear that across continents and plantation systems both human and environmental communities are impacted. The balance between positive and negative effects is likely to be dependent on the location and scale of the plantation being studied, and the ways in which the plantation is managed (Dislich *et al* 2015).

Oil palm is a major agricultural commodity produced in 43 countries across five continents (Miettinen *et al* 2012). While oil palm's range is restricted to the humid topics, regions may differ greatly in both ecological and social cultivation context, such as native species present or the employment history of local communities. Therefore, management suggestions may not be transferable across areas, and research and conservation efforts must incorporate strategies tailored to the specific location context (Vijay *et al* 2016). The ecological, social, and production sustainability of plantations are also heavily influenced by management decisions, including factors such as intercropping, chemical inputs, and implementation of certification schemes. As these vary widely between plantations and are often not optimal, the global average yield of 3.5 tons of oil per hectare (t) is far below the predicted potential of 11–18 tons (Barcelos *et al* 2015). For example, the yield gap between industrial and smallholder plantations can be as high as 40% (Molenaar *et al* 2013). Industrial plantations are managed by large companies and occupy thousands of hectares, while smallholder plantations are typically run as family farms (Bennett *et al* 2019). Assisted smallholders, also known as plasma or nucleus systems, are independent owners of the plantation but are associated with large companies for technical assistance. Due to their distinct operational scales, management between these systems differs. Industrial systems are often high-input monoculture plantations, whereas smallholders are frequently backyard polyculture plantations, lacking infrastructure (Bissonnette and De Koninck 2017). The scale of production and individual management decisions therefore has profound impacts on not only the ecology of oil palm landscapes, but on the social dynamics of owners and laborers.

As a multi-faceted and urgent global issue, the development of more sustainable palm oil production requires an innovative and integrated approach, involving numerous stakeholders and interacting components, with solutions and insights drawn from multiple disciplines (Miller 2016). This demands further ecological and social research, but also greater prioritization of interdisciplinary research that integrates multiple factors. The number of interdisciplinary research projects within agricultural systems is increasing (Kirsten 2008, Spelt *et al* 2010), with their importance highlighted by the Sustainable Development Goals framework (United Nations 2015). In this paper, we are focusing solely on socio-ecological research as interdisciplinary work. In socio-ecological studies, 'social' research projects are those in the field of social sciences, focusing on humans and their values, preferences, perceptions and decisions (Yousaf 2012). 'Ecological' research projects are those which study organisms, the environment, and their relationships. This includes the study of plant and animal populations, communities, and ecosystems, and includes all forms of biodiversity. Within each discipline, there are numerous potential study focuses and methodologies by which to conduct research. To achieve truly interdisciplinary socio-ecological research, information, methods, and perspectives must be integrated and synthesized throughout the entire research process (Beichler *et al* 2014). Previous reviews have called for further investigation into interdisciplinary work in globally important crops (van Noorden 2015), but the current status of interdisciplinary socio-ecological research on oil palm is unknown. To understand the breadth and depth of current socio-ecological research within oil palm, a mapping review is required.

This paper takes a systematic mapping approach with the primary objectives to:

- Determine how the number of ecological, social, and socio-ecological studies on oil palm cultivation has changed over time;
- Identify the prevalent study contexts and interventions in ecological, social, and socio- ecological research on oil palm cultivation, and how they have changed over time;
- Examine the differences and similarities in common research context, study methodology, and intervention focus between ecological, social, and socio-ecological studies on oil palm cultivation;
- Identify gaps in the evidence base that represent research priorities.

2. Methodology

We used a systematic mapping approach to quantify the amount of existing social, ecological, and socio-ecological research about oil palm cultivation and to identify gaps in the literature. Systematic mapping uses a detailed and established procedure to identify, classify, and describe a body of evidence (James *et al* 2016). In systematic maps, the quality of the evidence is not always appraised ('critical appraisal'), but instead they provide a measure of the current extent to which research has been conducted. Our methods were adapted from Collaboration for Environmental Evidence Systematic Review Guidelines (Pullin *et al* 2018), reporting standards for systematic evidence syntheses systematic map protocols (Haddaway *et al* 2018), and Cambridge Conservation Evidence Guidelines (Shackelford *et al* 2019). A stepwise approach was applied for the search process, based on the flow diagram for systematic maps detailed in the preferred reporting items for systematic reviews and meta-analyses ((Moher *et al* 2009) figure 1, supplementary information A). This approach involves a search of multiple databases, removal of duplicates, and evaluation of relevance at the title, abstract, and full-text level.

2.1. Setting of the search string

Before the initial search or setting of a search string, a set of ten 'benchmark papers' were selected through consultation with eleven experts in oil palm research (supplementary information B (available online at stacks.iop.org/ERL/6/063002/mmedia)). The experts included participants in high-profile oil palm research studies and academics with expertise in the topic. The benchmark papers represented the ten most-commonly suggested publications exemplifying interdisciplinary research on the socio-ecological effects of oil palm cultivation. These papers were then used to set and verify the search string, as described below.

The search string consisted of three parts: defining the subject (oil palm), defining the context of the intervention (at cultivation stage from planting to harvest), and defining the outcome (ecological, social, socio-ecological). We constructed three distinct strings to produce three distinct searches: the ecological effect of oil palm cultivation, the social effect of oil palm cultivation, and the socio-ecological effect of oil palm cultivation (table 1). The terms in the search string were determined through a review of titles, abstracts, and keywords in the benchmark papers, resulting in 16 core terms. Next, we conducted a search for synonyms and alternative spellings for these terms using the Oxford English Dictionary (Oxford University Press 2020), which gave a total of 73 potential terms. We then used these in a scoping exercise using ISI Web of Science in which we eliminated terms that contributed less than 1% relevant articles from a subset of results. The resulting 32 relevant search terms were then linked using the Boolean operators 'OR' and 'AND'. We considered the search string verified when all benchmark papers were located using these terms.

2.2. Searches

We searched peer-reviewed journals using ISI Web of Science on 15 January 2021. A total of 4696 articles were retrieved using the three search strings before duplication was accounted for: 2203 from the ecological search, 1478 from the social search, and 1015 from the socio-ecological search. A large amount of interdisciplinary research in particular is reported in 'grey literature', such as reports and doctoral dissertations (Lawrence *et al* 2015). Grey literature was found through the search engine EThOS (E-Theses Online Service, The British Library 2020), Open Grey (INIST-CNRS 2020) and a manual search of the referenced literature from the benchmark papers

Table 1. Search strings used for the three independent searches on Web of Science. In an advanced search, 'TS' defines the topic terms for the search, and an asterisk (*) is a truncation which retrieves words with variant zero to many characters (i.e. disease* will include diseases, diseased, diseasing, diseasedness, etc).

Search focus	Search String
Ecological	TS = (oil palm OR palm oil OR elaeis guineensis) AND TS = (agricultur* OR cultivat* OR crop*) AND TS = (ecosystem* OR environment* OR ecolog* OR habitat OR biodiver* OR divers* OR function* OR deforest* OR conservation OR sustainab*)
Social	TS = (oil palm OR palm oil OR elaeis guineensis) AND TS = (agricultur* OR cultivat* OR crop*) AND TS = (socio* OR attitude* OR choice* OR perception* OR decision OR preference OR behavio* OR knowledge OR income OR livelihood* OR wellbeing OR well-being OR welfare OR development OR household OR farmer*)
Socio-ecological	TS = (oil palm OR palm oil OR elaeis guineensis) AND TS = (agricultur* OR cultivat* OR crop*) AND TS = (ecosystem* OR environment* OR ecolog* OR habitat OR biodiver* OR divers* OR function* OR deforest* OR conservation OR sustainab*) AND TS = (socio* OR attitude* OR choice* OR perception* OR decision OR preference OR behavio* OR knowledge OR income OR livelihood* OR wellbeing OR well-being OR welfare OR development OR household OR farmer*)

using a 'snowball design'. The 'snowball design' entails compiling the relevant publications from the benchmark papers' bibliographies, and then searching the citations of the resulting publications for additional relevant works (Naderifar *et al* 2017). Snowball sampling was complete when there were no new relevant publications produced. We also searched the bibliographies of key review papers (Fitzherbert *et al* 2008, Foster *et al* 2011, Obidzinski *et al* 2012, Savilaakso *et al* 2014, Dislich *et al* 2017, Qaim *et al* 2020) for relevant titles, resulting in 147 new titles. After removing 711 duplicates, 5232 unique titles remained (figure 1, supplementary information A).

2.3. Inclusion/exclusion

Retrieved publications were screened in three stages: title only, abstract and, where necessary to gain the complete classification information required, full text. When screening articles for relevance, a series of inclusion and exclusion criteria were consistently applied (table 2). Exclusion criteria were set following Methley *et al* (2014), using an adaption on the PICOS review model: population, intervention, comparator, outcomes, and study design. In the PICOS model, population is the research subject, intervention is the potential action or decision being studied, comparator is the type of comparisons the study makes, outcome is the effects of the intervention on the population, and study design is the type of research included in the review (Pullin and Stewart 2007). We only included publications which: (a) focused on the ecological and/or sociological effects of oil palm cultivation (b) investigated the effects of interventions applied only at the cultivation stage of oil palm production (c) reported primary studies. No date restriction was applied and, due to resource constraints, only publications available in English were considered.

Prior to exclusion screening, a trial screening was conducted with a second researcher on 10% of search results. To avoid interpretive bias, the two researchers came from different backgrounds but both worked in the relevant field of oil palm research (MacCoun 1998). An inter-reviewer consistency check was conducted at both the title and abstract stage using Cohen's Kappa (k) (Carletta 1996). If a discrepancy occurred, the publication was marked and saved for later examination and discussion. From these discussions we adapted and clarified the inclusion/exclusion criteria (table 2). The initial Cohen's k value was 0.47 after screening of 100 titles. When the exercise was repeated, a Cohen's k value of 0.740 was reached at title and 0.843 at abstract level, exceeding the frequently used guideline of 0.60 (Collaboration for Environmental Evidence 2013).

After screening titles, 1107 of the 4959 records remained (figure 1, supplementary information A). These publications were further refined using the same inclusion/exclusion criteria to examine abstracts. After abstract screening, 453 items remained. Due to the high volume of relevant literature captured and resource limitations, the full article was only examined when there was doubt about relevance or to obtain additional classification information necessary for this publication. Ten publications where no full text was retrievable were removed, and the remaining 443 publications continued onto classification (supplementary information C).

2.4. Classification and coding

Keywords were used regarding common interventions, comparators, study scopes and outcomes to describe, classify, and code publications. The interventions, comparators, study scopes and outcomes used for classification based upon the same concepts in the inclusion/exclusion criteria (table 2). The initial keywords were determined through our knowledge of oil palm research and listing the common topics and research methodologies seen from the benchmark papers. To expand on these categories, we read the abstracts of the first 100 socially focused

Table 2. Table of inclusion and exclusion criteria for retrieved publications.

Search element	Inclusion	Exclusion
Population (subject)	Studies on some aspect of ecology and/or sociology on oil palm plantations and their surrounding environments (terrestrial and aquatic). Inclusive of studies conducted in all countries.	Studies on other crops, genetic or cell research.
Intervention	All interventions with an intent to affect ecological or sociological factors, carried out at the cultivation stage of palm oil production. All actions taken by researchers, farmers, industrial owners, or other involved participants are included. This includes, but is not limited to, inputs such as fertilizer and herbicide application, implementation of certification schemes, government interventions to increase female involvement, and choices made regarding cropping and planting structure.	Interventions at other stages along the line of production, including the processing or consumption stages.
Comparator (context)	Both comparative and non-comparative studies were included. Comparisons included: comparisons over time, comparisons between control and intervention groups, comparisons between interventions, comparison with other land uses (forests, other crops).	
Outcome	Any measured effect on ecological and/or sociological factors. Effects of cultivation on any biotic or abiotic component of the ecosystem were considered, including greenhouse gases and water systems. Effects on sociological factors included the effects of oil palm cultivation on farmer livelihood, attitudes towards nature, or food security.	Effects on elements outside of the cultivation area, on country GDP, or regional deforestation rates.
Study design	Only primary research studies were included. Correlative and manip-ulative studies were included.	Predictive models, frame-works for methodology or new research approaches, review papers, or narratives.
Date	No date restrictions were applied.	
Language	English only,due to resource constraints.	

and first 100 ecologically-focused records, ordered alphabetically, to extract prevalent research themes. This resulted in 39 initial categories. The authors of the ten benchmark papers provided feedback on the proposed classification scheme and suggested adding nine additional categories. For clarity, we organized themes into three distinct 'ecological', 'social', and 'study focus' categories (figure 1). Within this, a hierarchy of themes was developed, with each culminating in a final level used to classify the publications (hereafter referred to as 'code'). Studies were able to fit into multiple categories and were assigned all of their relevant codes across all sections. Country in which the study was conducted was also recorded for each publication.

2.5. Data visualization and analysis

Data manipulation and visualization was done in R and using R studio (R Core Team 2020, RStudio Team 2020). The package ggplot2 was used for data visualization of trends in the literature (Wickham 2016). We used the packages ggplot2, reshape2 (Wickham 2007), and cooccur (Griffith 2016) to construct heatmaps.

3. Results

3.1. Characteristics of included studies

3.1.1. Distribution of publications and disciplinary focus over time

The first study identified in the initial search before screening was published in 1980, with the first relevant study published in 1993 (figure 2). A total of 371 relevant studies were published between 1993 and 31 December 2020. Over 70% of publications were purely ecologically focused, with 19% focused just on social disciplines and less than 10% of studies including components of both disciplines. There has been a rapid increase in relevant publications over time. Between 1993 and 2000, only eight relevant studies were produced, seven of which were ecologically focused, and one of which mentioned both social and ecological factors. In the next decade, 55 relevant papers were produced, once again with the majority (76%) being ecologically focused.

In the past 10 years there has been a large increase in the number of publications produced, with 86% of relevant studies conducted since 2010. The number

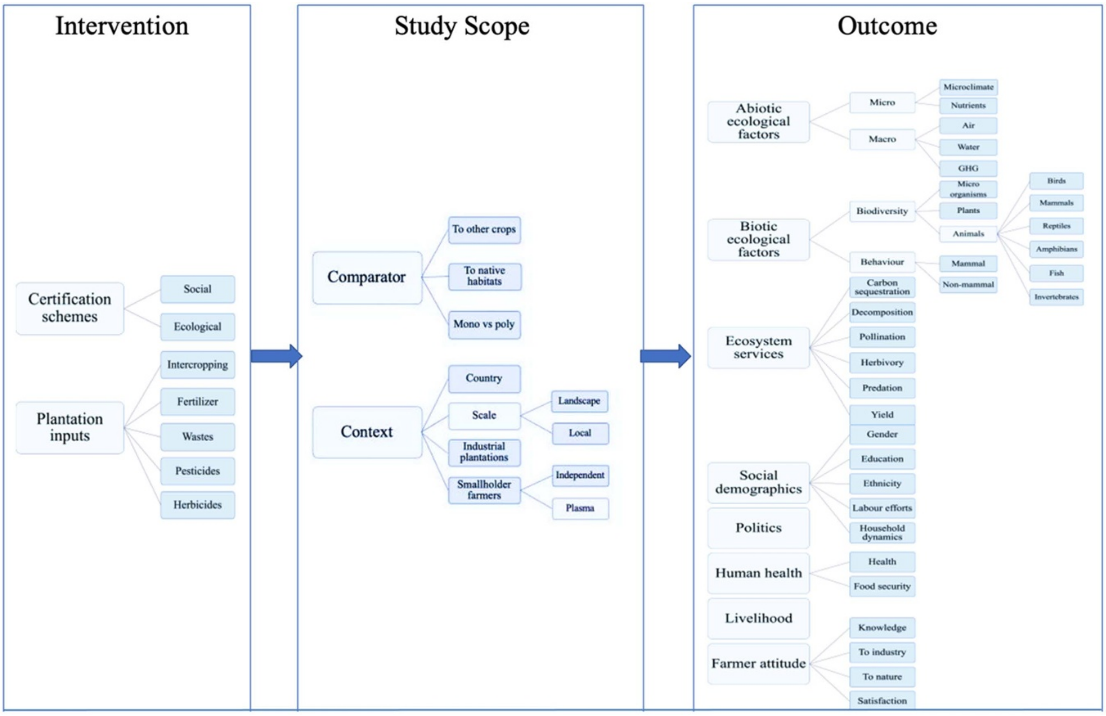

Figure 1. Coding used in classification of publications per 'Intervention', 'Study scope', and 'Outcome'. The categories at the end of their hierarchical line in darker blue are the ones used for final classification ('codes'). GHG—greenhouse gases, mono vs poly—monoculture versus polyculture.

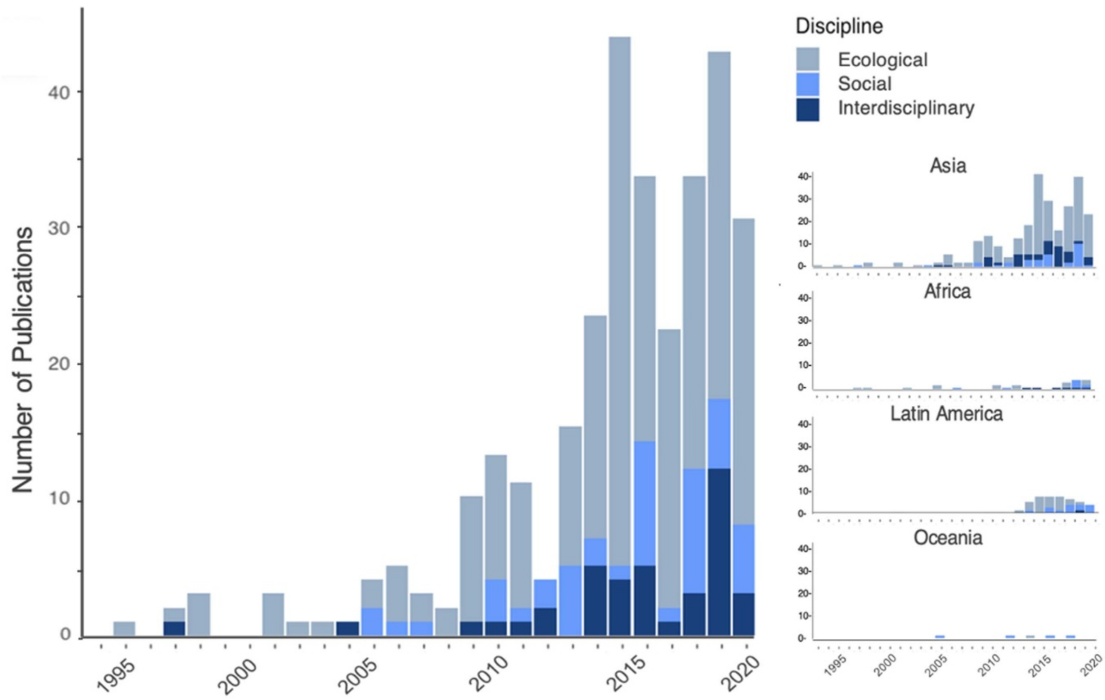

Figure 2. Stacked bars show changes in the focus of research on oil palm cultivation between 1993 and 2020. The number of relevant publications retrieved is separated by disciplinary focus. Insert shows the number of publications and change in disciplinary focus in each region over time.

of interdisciplinary socio-ecological studies has also accelerated, with more interdisciplinary studies produced in 2019 alone (12) than were conducted in the 20 years from 1993 to 2013 (figure 2). In the past 5 years approximately 10% of publications were interdisciplinary.

For all regions, the majority of studies focused on the ecological effects of oil palm cultivation. Over

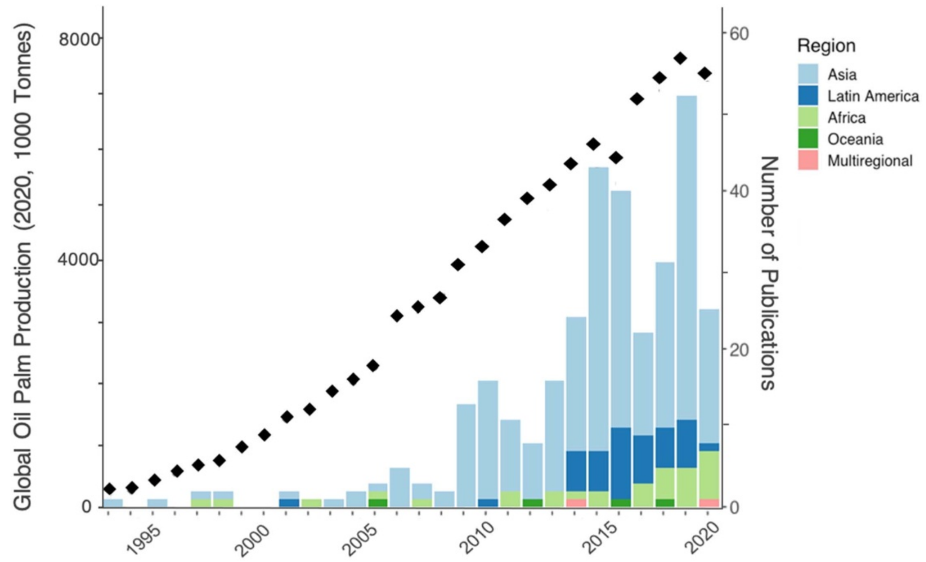

Figure 3. Stacked bars show the number of publications on oil palm cultivation between 1993 and 2020, separated by geographical region of study. The overlying points show global annual palm oil production in 1000 tons between 1993 and 2020 (FAO 2020). Source: Food and Agriculture Organization of the United Nations. Reproduced with permission from FAO (2020).

70% of studies in Asia, 71% of studies in Latin America, 50% of studies in Africa, and 72% of studies in Oceania focused on ecological outcomes. The majority (75%) of the 40 interdisciplinary studies were conducted in Asia.

3.1.2. Distribution of geographical focus over time

The first relevant study was conducted in Asia, with a five-year gap until a publication was conducted in another region (Africa in 1998). All regions saw increases in publications after 2010 (figure 3). Approximately two-thirds (326) of all 443 studies were conducted in Asia, with approximately 15% of studies performed in Latin America, 8% in Africa, 1% in Oceania, and only two publication containing research conducted in multiple regions (figure 3). Both global palm oil production (FAO 2020), and total number of publications increased from 1993 to 2020 (figure 3). The lowest year for production (1993), was also the lowest year for publications. Similarly, the highest year for production (2019), was the highest year for publications.

Inclusive of all disciplines, 161 studies occurred in Malaysia and 145 in Indonesia, contributing 36% and 33% of all studies respectively (figure 4). The third most common study country was Brazil, with 21 studies. Six Asian, eight Latin American, nine African, and one Oceanic country were represented in the data set. Nicaragua, Panama, Senegal and Tanzania were each represented with only one publication. Nearly twice as many studies were conducted in Malaysia in 2019 alone as were conducted in the whole of Africa from 1993 to 2020.

Overall, publication levels across countries reflected palm oil production patterns following the Food and Agriculture Organization (FAO) rankings from 2018 (FAO 2020), but with several key differences. For example, there were more publications from Malaysia than Indonesia, although Indonesia currently has higher palm oil production. The third highest producing country, Thailand, was only seventh in research publications. Nigeria was fourth in global production, but had fewer publications than 15 other countries. The three lowest producing countries that were included in the literature were Guinea Bissau, Senegal, and Sri Lanka. The seventh (Ecuador), eighth (Cote d'Ivoire), and ninth (Honduras) highest palm oil producing countries were not represented in the literature.

3.1.3. Occurrences of varying study scopes

The most common study context was industrial plantations, representing 53% of the 377 publications where plantation type was specified (figure 5). Thirty-five percent of publications involved on independent smallholders, with the remaining 12% of publications referencing plasma smallholders. Fourteen percent of the 443 publications did not mention the type of plantation being studied at any point in the full text. Most interventions were investigated at a local scale (57%), which reflects smaller scale within-farm interventions, as opposed to wider landscape scale interventions. The interventions most commonly studied were fertilizer application (35% of intervention studies), contributing more studies than all other direct management inputs (waste application, pesticide usage, herbicide usage) combined (figure 6). Certification programs were investigated 18 times, with majority of investigations (64%) reporting on ecological effects. In 64% of

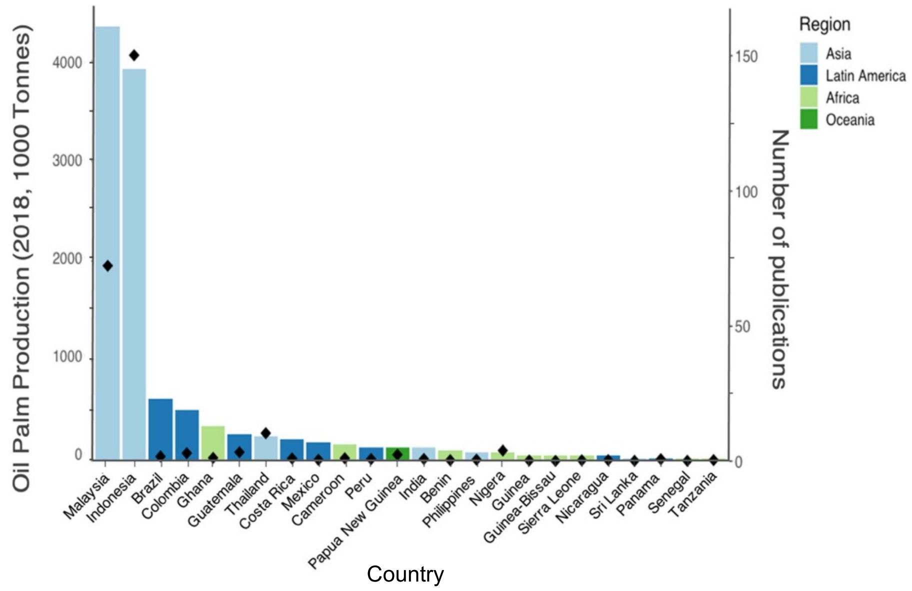

Figure 4. Bars show the number of publications on oil palm cultivation carried out in each country from 1993 to 2020. The overlying points shows the annual production of palm oil for each country in 2018 in 10 000 tons (FAO 2020). Source: Food and Agriculture Organization of the United Nations. Reproduced with permission from FAO (2020).

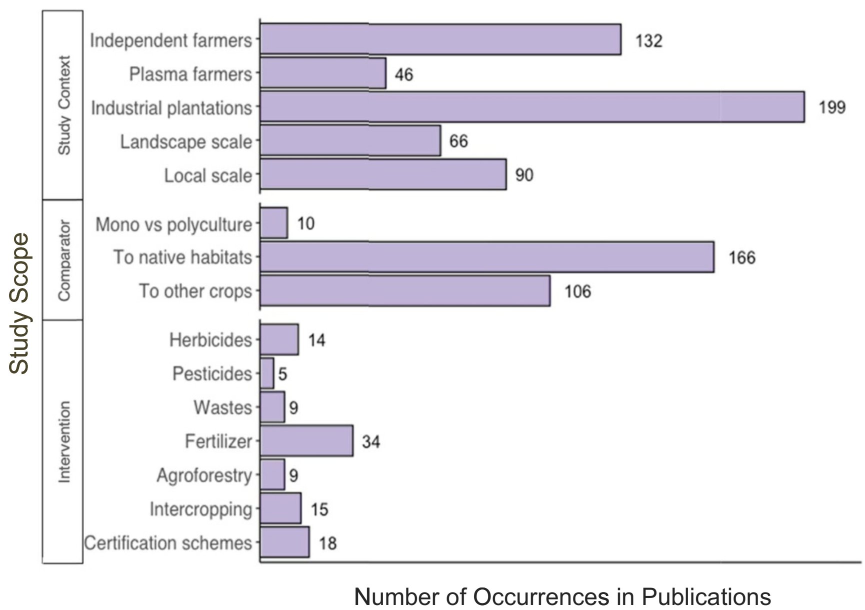

Figure 5. Study context, comparator, and intervention codes and their respective occurrences in publications. Publications can appear in more than one code, as the overall study scope often includes several factors. Publications were not required to contain a context, comparator, or intervention, and some studies are not represented across these codes. Codes are organized according to the 'Intervention', 'Comparator' and 'Study Context' groupings determined in methodology—see figure 1.

publications, a comparator was used. Of these studies, the most common comparator was native habitats (59%), with comparisons to other crops also common. Fifty-eight percent of studies compared oil palm to rubber cultivation, and 7% to other tropical biofuel crops, including cassava, jatropha, and sugarcane. Comparisons between mono and polyculture plantations were rare, with only ten studies identified.

3.1.4. Outcomes examined

The outcomes most frequently reported were effects on farmer livelihood (75), yield (74), invertebrate biodiversity (72) (figure 7). Overall, social outcomes were reported in 35% of publications, with ecological outcomes reported either independently or in combination with other outcomes in 65% of publications. Data on biodiversity were reported 1.5

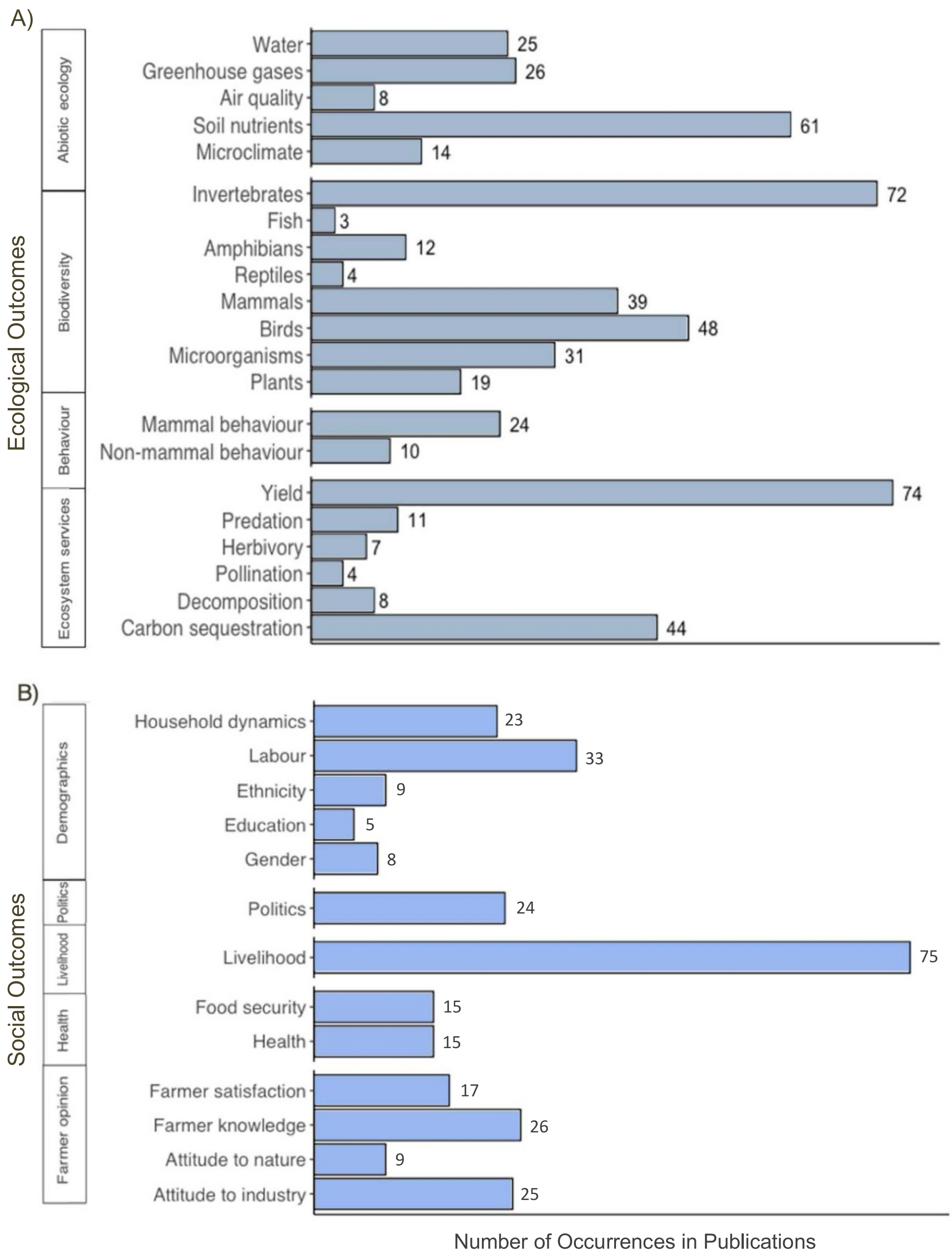

Figure 6. Frequency of outcome factors examined in all included publications. As many studies examined more than one outcome, articles can appear in more than one code. (A) Frequency that each ecological outcome was examined in publications. (B) Frequency that each social outcome was examined in publications. Codes are organized according to the groupings determined in methodology—see supplementary information A figure 1.

times more frequently (228) than data on ecosystem services (148). Of the 228 biodiversity publications included, studies were most commonly conducted on invertebrates (32%), birds (21%), and mammals (17%). Behavioral studies focused on mammals 70% of the time they occurred. Of the 148 publications on ecosystem services, the most commonly investigated ecosystem services were yield (50%), and carbon sequestration (29%), with all other services combined contributing approximately 20% of reported ecosystem service outcomes. Pollination was studied most rarely of the ecosystem services. The most frequently mentioned social outcome was livelihood (75). Demographic factors were mentioned 78 times within the studies, with over 42% of occurrences coming from studies on the effects of cultivation on labor dynamics. Farmer opinion was recorded 77 times, with

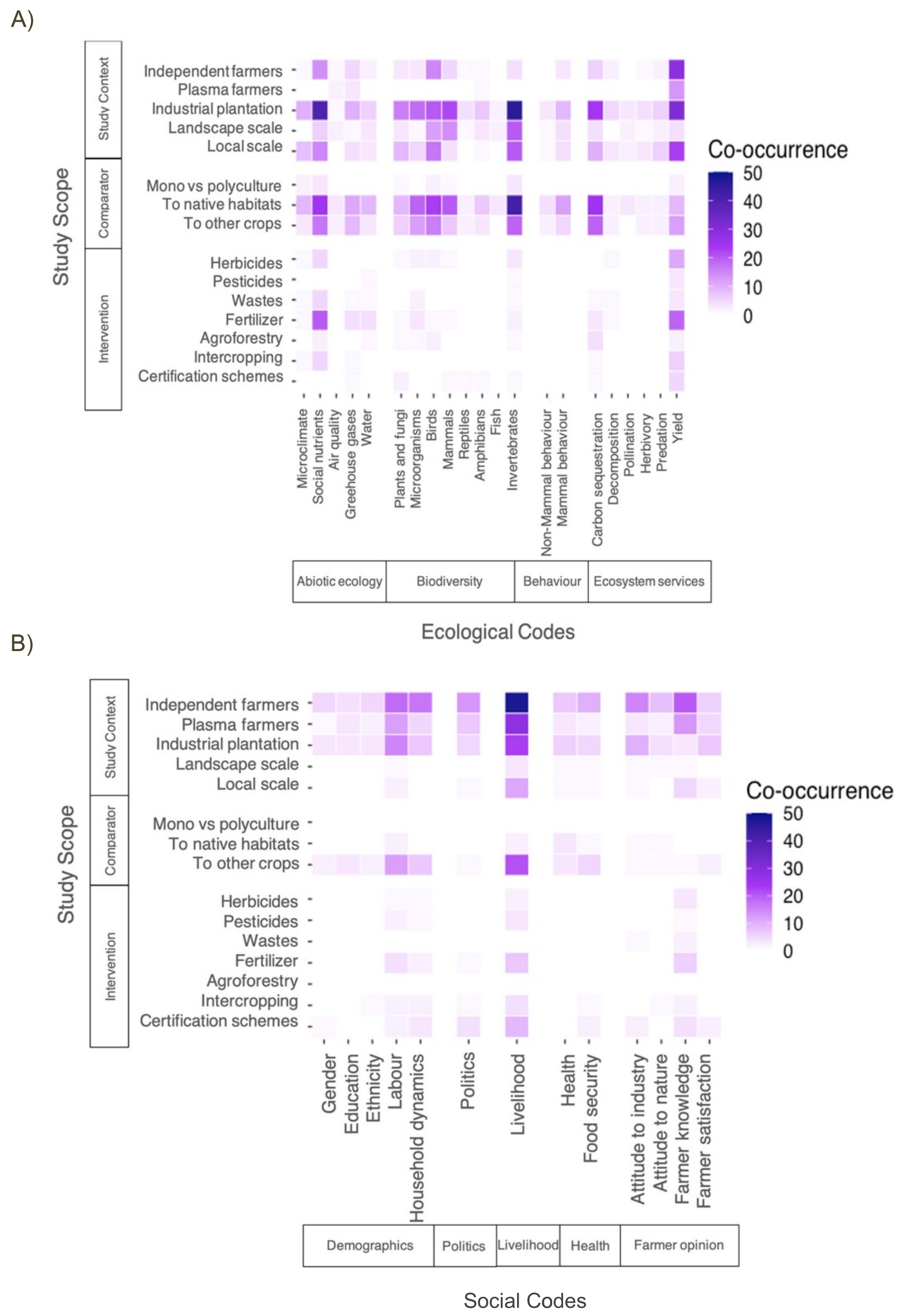

Figure 7. The linkage between study scope and outcome examined for the 443 publications. (A) Co-occurrences in the relevant literature of study scope factors and ecological outcomes. (B) Co-occurrences in the relevant literature of study scope factors and social outcomes. The color of cells reflects the total number of articles retrieved with each scope/outcome combination. The darker the color of the cells, the higher the frequency of articles. An individual publication can fall into multiple cells. Codes are organized according to the groupings determined in methodology—see supplementary information A figure 1.

attitude towards industry (32%) and farmer knowledge (33%) more frequently investigated than farmer satisfaction (122%) and attitude towards nature (12%).

3.2. Co-occurrence of study scope and outcomes

In ecological studies, industrial plantations were investigated nearly 1.5 times more frequently than smallholder plantations (figure 6(A)). Plasma farms only contributed 5% of ecological publications. Ecological outcomes were studied twice as often at a local scale than on a landscape scale. The most common comparator and outcome combination was studies on invertebrate biodiversity in oil palm plantations compared to non-modified habitats (31 studies). The next most common combinations were on carbon sequestration (25) and bird biodiversity (23) versus native habitats. Comparisons to native habitats contributed 60% of comparative ecological studies. Comparisons of the ecological effects of mono or polyculture plantations were rare, with only 14 occurrences. The most common combination of interventions and

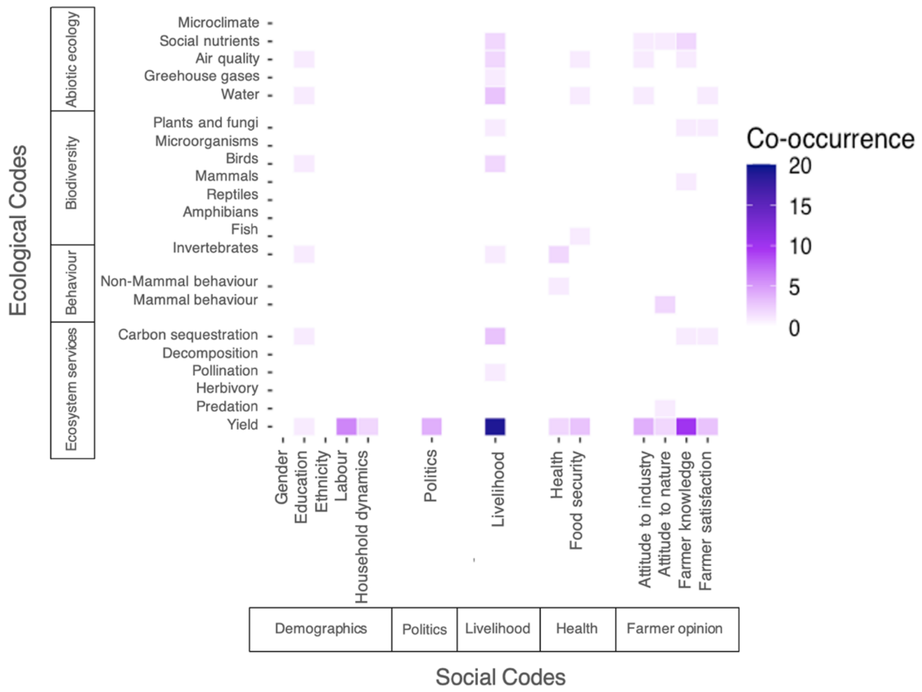

Figure 8. The co-occurrence of ecological and social outcomes in the 443 publications. The color of cells reflects the total number of articles retrieved with each social/ecological combination. The darker the color of the cells, the higher the frequency of articles. An individual publication can fall into multiple linkage cells. Codes are organized according to the groupings determined in methodology—see supplementary information A figure 1.

ecological outcomes was the effect of fertilizer on soil nutrients (20), and fertilizer on yield (19). These were the only two combinations of outcome and intervention that were seen more than ten times in the literature. Studies on the effect of any of the interventions on fish biodiversity were absent, and the effects of interventions on reptile or amphibian biodiversity were seen only once. The only ecosystem service effect of certification schemes were effects on yield and carbon sequestration, and carbon sequestration was only studied twice in this scope. There were no publications on the effect of any of the seven interventions on pollination, herbivory, or predation. All interventions were studied more than twice as often for ecological outcomes as for social (figures 6(A) and (B)).

In contrast to ecological studies, the most common plantation type used for social studies were independent smallholder plantations (49%) (figure 7(B)). Industrial farms were slightly more frequently used (26%), than plasma plantations (24%). A local scale of investigation was also more common than landscape scale in social studies. Far fewer studies used comparators for social concepts than ecological, with co-occurrences across all potential combinations more than five times more common in ecological studies (figure 6). In the studies that used comparators for social outcomes, comparisons to other crops were most common (61%). There were no studies comparing the effects of mono- versus poly-culture cultivation on social outcomes. Gender, education, human health, and attitude toward nature were not seen in combination with any of the seven interventions. The most common intervention and social outcome combinations were fertilizer and livelihood (7), and fertilizer and farmer knowledge (6). The effects of certification schemes as an intervention were studied over five times more frequently for social outcomes than for ecological outcomes. Gender, education, human health, and farmer satisfaction were not seen in combination with any of the seven interventions.

3.3. Co-occurrence of ecological and social dimensions

The most commonly occurring combinations of social and ecological outcomes were livelihood and yield (19), farmer knowledge and yield (10), and labor dynamics and yield (6) (figure 8). Yield was the most frequently occurring outcome in interdisciplinary studies, seen in 52 publications. Livelihood was the most common social outcome in interdisciplinary studies (35), with farmer knowledge the next most frequent (16). Gender, ethnicity, microclimate conditions, reptile, plant and amphibian biodiversity, herbivory and decomposition were all absent from any interdisciplinary studies. Labor, household dynamics, politics, and attitude towards industry only occurred in interdisciplinary studies when in conjunction with yield. Of a potential 273 interdisciplinary combinations, only 42 occurred. Of these 42, only 17 combinations were found in more than one publication.

4. Discussion

Our study provides an up-to-date map quantifying the current status of ecological, social, and socio-ecological research on oil palm cultivation. We identified a recent surge in the number of publications across disciplines and continents, but a continuing lack of interdisciplinary studies and a propensity towards publications based in Asia. Disciplines differed in study scope, with research conducted more commonly in industrial plantations for ecological studies but in smallholder plantations for social studies, and comparisons to native habitats being the most common study focus in ecology but comparisons to other crops more common in sociology. We found that the majority of research was focused on ecological outcomes, with a clear bias towards biodiversity and yield, and a lack of focus on other essential ecosystem services such as pollination and herbivory. In social research, livelihood was heavily studied, with further information required on food security, gender and ethnic equality, and farmer well-being required to provide valuable management suggestions. Interdisciplinary research rarely went beyond yield as an ecological outcome. While most potential interdisciplinary combinations were not found, we acknowledge that not all 'knowledge gaps' will provide valuable information for sustainable management, and therefore may not warrant being filled. We have determined which research areas are of highest priority through their potential to resolve known issues in sustainable agriculture. Although this study was limited to English language and only three databases due to logistical constraints, it represents the most extensive evidence mapping exercise of the interdisciplinary oil palm plantation literature to date and is a valuable resource for directing future research.

4.1. Changes in study focus and geographical location over time

Our results show a clear increase in the number of studies on oil palm since 1993, with the vast majority of research being conducted in the past 10 years (86% of publications). While ecological research consistently dominates the literature, social and interdisciplinary research has increased in the past decade. Despite this, socio-ecological studies are still rare and make up only 10% of publications in the past 5 years. This focus on ecological studies contrasts with the relative weighting given to ecological and social factors in palm oil sustainability schemes. For example, of the 41 sustainability criteria identified by the RoundTable on Sustainable Palm Oil (RSPO), the world's largest sustainability certification scheme, 17 include ecological concepts and 29 social concepts (RSPO 2018). Humans and the environment are fundamentally linked and, therefore, an understanding of the interdisciplinary factors at play is required to fully address urgent sustainability concerns (Liu *et al* 2007). The importance of socio- ecological research in agriculture to inform more sustainable production has also been highlighted by the United Nations' Sustainable Development Goals (United Nations 2015). We have established that research efforts are increasing in this area, but they remain rare, potentially hampering development of more sustainable cultivation across broad ecological and social criteria. The biases identified above were similar across all regions where studies had been conducted. This indicates that researchers may be following a similar focus, regardless of area and may not be considering the cultivation context and pressing concerns of each region. For example; in Africa, 90% of production is contributed by smallholders, compared to 40% in Indonesia (DJP 2015), suggesting that there should be a greater research effort devoted to smallholder cultivation in this region.

Palm oil production has greatly increased in recent years, nearly doubling between 2003 and 2013 to meet rising demand as an ingredient in food, cosmetics, and household cleaning products, as a cooking oil, and as a biofuel source (Pirker *et al* 2016). Currently, palm oil accounts for over one-third of global vegetable oil consumption, with production increases expected to continue (FAO 2018). A steady increase was seen both in global palm oil production and number of publications in our study years of 1993–2020. Southeast Asia overtook Africa in production capacity in 1966 (Poku 2002), with Indonesia and Malaysia currently accounting for over 85% of the global palm oil production (Cassiday 2017). More recently, production has increased in Latin America and Africa (Potter 2015). This global pattern is largely reflected in the geographical location of studies, with 70% of publications being conducted in Indonesia and Malaysia. However, research is not always in line with production trends. The first year with multiple publications based in Latin America was 2014, with research lagging behind the doubling in oil palm production in the region from 2001 to 2017 (Furumo and Aide 2017). Only five studies were conducted in Peru, although the country quadrupled its production from 2000 to 2013 (Bello 2015), illustrating a lack of consideration of individual county production levels within regions in targeting research effort. Similarly, Sub-Saharan Africa now accounts for over a quarter of the world's land area devoted to oil palm (Ordway *et al* 2019), but we found fewer than 8% of publications had been conducted in this region. Three of the top ten global producers of oil palm (Ecuador, Cote d'Ivoire, Honduras) were not represented in the literature, showing a lack of comprehensive knowledge on the impacts of oil palm in these countries. There is, therefore, a clear need for more research to be undertaken in less-studied regions and countries. This is especially important as areas differ substantially in their ecological and social contexts, meaning that findings from one area cannot necessarily be applied to another. For example, the native habitat used in comparative studies is often forests in Southeast Asia, whereas grasslands are common native habitats in Latin America (Mutsaers 2019). Therefore, studies on post-conversion management in Malaysia are not necessarily relevant to plantations in Mexico, and an understanding of local context is needed. In some cases, the lack of research may be due to inadequate funding or difficulty in safely obtaining research access. Therefore, work should also be carried out to seek novel opportunities to increase this research activity, for example by facilitating research and data gathering by oil palm growers themselves.

4.2. Research scope

The majority of research (53%) has been undertaken on industrial plantations. An estimated 18.7 million ha of land is devoted to industrial oil palm production worldwide (Meijaard *et al* 2018), and this remains an important study context. The 35% of studies on smallholder plantations largely mirrors the 41% of production from these farmers (RSPO 2018). When examined at a disciplinary level however, there was a clear bias for studies on industrial plantations in ecological research, whereas social studies were more frequently conducted in independent smallholder farms. As smallholder farmers both directly impact and are impacted by their plantations, social outcomes are likely to have a greater importance in smallholder contexts, representing a logical explanation for this pattern. However, because of this discrepancy in plantation type used in ecological versus social studies, it is possible that conclusions drawn from the literature on the overall impact of oil palm cultivation may be biased. Plasma farms, those owned by individuals but coordinated as large-scale cooperatives, were rarely used in ecological studies (5%). As plasma farming aims to increase production capabilities and sustainability of plantations (Jelsma *et al* 2017), research is needed to quantify the social and ecological impacts of such production systems and to determine if such systems are truly beneficial. We call for more work that specifically examines differing impacts of ecological studies in smallholder systems and social studies in industrial plantations.

Production trends and country cultivation context must also be considered when determining appropriate study scope. In Africa, oil palm is traditionally grown as a smallholder polyculture crop, and in Ghana smallholders currently occupy over 75% of land devoted to oil palm. Thus, a bias for smallholder research in the region would be appropriate. Even within regions, a context-conscious approach is necessary. For example, within Latin America, production in Peru largely consists of industrial plantations, while plantations in Mexico are mostly the result of smallholder conversion of pastures to oil palm (Furumo and Aide 2017). The changing focus of production trends must also be considered. Researchers estimate that Indonesian independent producers will double their production by 2030 and manage 60% of Indonesia's area under cultivation (Meijaard *et al* 2018), indicating that research within independent smallholder plantations will become increasing relevant in Indonesia in the future. To understand the potential effects of cultivation and to inform scientifically supported management recommendations, research therefore needs to be tailored to the region, both currently and following projected trends. The majority of existing studies have taken a case study approach, which may limit understanding of cultivation effects at large spatial and temporal scales. While case studies allow in-depth investigation of relationships between variables, it is difficult to standardize and scale their results for applicable recommendations at a global crop. A research focus at the plantation and landscape scale may compromise holistic understanding of cultivation impacts on concepts such as agroecosystem functioning (Swift *et al* 2004). To truly understand the effect of management practices and policies, large scale counterfactual studies are required, complementing case studies, and allowing comparisons of environmental and social outcomes between areas with and without oil palm, or with and without particular interventions.

In studies with comparators, most comparisons were drawn between plantations and native habits, such as forests or savannahs (60%). The lower ecological value of plantations compared to native forests has been well established, particularly in Malaysia and Indonesia (Fitzherbert *et al* 2008, Obidzinski *et al* 2012, Dislich *et al* 2015). Our research suggests there is little need for further comparison studies with forests in well-studied taxa, such as invertebrates and birds. Research investigating differences between management strategies, such as mono versus polyculture cultivation, was less common. For example, only ten studies focused on the ecological or social effects of plantation cropping strategies. Similarly, we found only 18 mentions of the social and/or ecological impact of certification schemes from 15 unique papers. Such schemes rely on consumers paying a premium to ensure environmental and social standards are maintained along the supply chain (Morgans *et al* 2018). There are currently five major certification schemes working towards sustainable palm oil: RSPO (Roundtable on Sustainable Palm Oil), ISCC (International Sustainability and Carbon Certification), ISPO (Indonesian Sustainable Palm Oil), MSPO (Malaysian Sustainable Palm Oil), and NDPE (No-deforestation, No-peat and No-exploitation) (McInnes 2017). All but one of these, RSPO, has been established in the past decade due to an increase in interest from producers, consumers, and governments in sustainable palm oil. Certification programs have been hailed by some as a potential path towards sustainability (Carlson *et al* 2018). Therefore, there is a need to further understand their direct effects and benefits (Padfield *et al* 2019). Work is currently increasing in this area; a recent paper by Santika *et al* (2021), although beyond the date limitations of our review, has addressed the social impacts of certification schemes. Recent interdisciplinary research on certification effects has also been conducted by Lee *et al* (2020). Taken together, our findings highlight that the most pressing and important research gaps to address are on the relative impacts of different cropping options and alternative management strategies, including recommendations specified within certification schemes. This work will provide the information necessary to inform the development of more-sustainable palm oil production.

4.3. Study outcomes

Invertebrate biodiversity was the most studied ecological outcome. This trend is mostly likely a result of the critical and widely acknowledged role invertebrates play in oil palm plantations, contributing to ecosystem services such as pollination and decomposition (Foster *et al* 2011). The results also revealed a clear outcome focus on yield, with yield investigated more than any other ecosystem service. Yield can be classified as both an ecosystem service and an economic output, hence this finding indicates a focus on the agricultural rather than ecological values of plantations. Furthermore, high yield is the priority aim of oil palm cultivation and can act as an integrated measurement of the health of other ecosystem services. If the ecosystem is functioning efficiently towards its agricultural aims, yield should presumably be high. Across ecosystem services, there is a clear lack of research on pollination, although previous studies have highlighted that pollination is crucial in maintaining yield and can vary over time (Li *et al* 2019). This gap in the literature may be related to the accepted wisdom that oil palm pollination relies only on the African oil palm weevil, *Elaeidobius kamerunicus* (Syed 1979). However, other species have been identified as being potentially important in oil palm pollination (Silva *et al* 1986), and a reliance on one species poses risks to the long-term productivity of the crop in a changing climate (Rao and Law 1998). As pollination contributes to both the ecological and economic wellbeing of plantations (Fijen *et al* 2018), an understanding of the effects of interventions such as herbicides and pesticides on pollinators is required to optimize management. A previous literature review highlighted the same result, suggesting a need for prioritization of pollination surveys (Dislich *et al* 2017). We found only four relevant publications on herbivory, which has implications for both yield and biodiversity. As 30%–40% of potential crop yield is lost due to pathogens and pests across major agricultural commodities (Oerke 2006), this also represents a pressing knowledge gap and should be a focus for future research. Indeed, damage due to pests and disease, as well as nutrient deficiency and insufficient water availability, have been identified as the major factors responsible for palm oil yields being below their theoretical maximum in plantations (Woittiez *et al* 2017). It is therefore clear that research efforts are lacking behind requirements in these areas. As a major agricultural commodity, suboptimal yield may affect both profitability and land use efficiency, and therefore has substantial ecological and social effects.

The most commonly investigated social outcome was livelihood, a broad term that describes the way one procures access to the basic necessities of life, for example, the way one earns money to pay for food and housing. The bias towards livelihood is understandable given its influence on health, security, and living standards. However, more information on components which influence and are influenced by livelihood, such as food security, gender equality, and education, may provide more distinct detail on the social impacts of cultivation due to their more focused outcome measures. Such directed research may more clearly identify management strategies to benefit social sustainability. However, measurement of outcomes such as household dynamics and farmer well-being often require a greater connection to the study population to retrieve accurate results, and therefore more time in the field, which may explain the lack of studies in these areas. As a caveat to these findings, the broad bias towards livelihood seen in the literature was partially also reflected in our classification scheme; due to the large number of potential outcomes, we were not able to consider all social concepts individually and so may have under-recorded their variation. Later research focused solely on social outcomes may be able to quantify the literature in a more nuanced way, picking apart livelihood and welfare concepts beyond education and food security. We found no research into the effects of chemical inputs on human health. This is concerning, as several studies in other crops have identified adverse long-term effects of pesticide use on farmer health, and indicates that this is a priority area for oil palm research, given the widespread use of chemical applications in this system (Christiansson 1991, Wilson 2000). There were no data on the effects of polyculture systems as opposed to monoculture, or on the effects of agroforestry systems on social concepts. Although these are ecologically-based interventions, both of these diversified planting strategies have been shown to increase health and well-being of farmers in other crops (Bacon *et al* 2012). To efficiently use limited intervention funds and effort, sustainable oil palm cultivation should make use of strategies which increase both ecological and social value, and thus research into these strategies is crucial.

Our results have shown that several combinations of interventions and outcomes are largely absent from the literature. However, research on some of these combinations may not be necessary in informing the development of ecological and socially sustainable oil palm cultivation. For example, studies quantifying how waste application affects education levels is a lower research priority than the effects that certification schemes have on farmer satisfaction. While livelihood is a valuable barometer for the social impacts of agriculture, a large amount of research has been done in this area. Studies on more discrete outcomes, such as food security, gender and ethnic equality, and farmer well-being are now required to further develop our understanding of social-sustainability components, and to allow focused management interventions to be developed.

4.4. Trends in interdisciplinary research

Interdisciplinary research can often provide a more holistic and broad understanding of human-environmental systems than single-disciplinary research, which has the limitation of focusing on unidirectional relationships. In this way, interdisciplinary research can provide greater understanding of effects with multiple components. For example, in a different agricultural system, an interdisciplinary project on cattle can investigate the effects of anti-parasitic medication on human health from consumption, milk yield and animal welfare, and effects on dung beetle biodiversity in the pastures (Finch *et al* 2020), whereas a single disciplinary project may consider only one factor, and thus produce less valuable management suggestions that take into account the full range of potential costs and benefits (Ostrom 2007). Interdisciplinary research can also investigate the effects of inputs from one discipline on the outcomes of another, for example the effect mammal biodiversity on the plantation may have on the attitudes of farmers to nature.

Of the 273 potential interdisciplinary outcome combinations, only 42 were found in the literature. As identified above, the most frequent socio-ecological outcome included in any publications was yield. The interaction between livelihood and yield was commonest, most likely because smallholder and plasma farmers' livelihoods are directly dependent on yield. Other common outcome combinations were related to human health. For example, several publications related human health to biodiversity and were largely based on mosquito-borne diseases and their prevalence in oil palm plantations. No literature was found relating human health to abiotic ecological factors, although air and water quality directly affects surrounding communities, highlighting this as a key knowledge gap in the literature. However, as a caveat to findings, our inclusion criteria specified effects of interventions only at the cultivation stage of palm oil production, and therefore excluded papers on large-scale deforestation rates and habitat change. This may have led to the exclusion of some interdisciplinary works related to oil palm, as deforestation has noted social and ecological effects (Carlson *et al* 2018, Heilmayr *et al* 2020).

4.5. Findings in context: previous reviews

Several major literature reviews have been conducted on the effects of oil palm cultivation. As oil palm literature has increased greatly in recent years, reviews conducted prior to 2010 only consider 10% of the currently available literature. The majority of the most highly cited publications have focused on ecological comparisons to native landcover and the negative impacts of conversion from forest (e.g. Fitzherbert *et al* 2008, Obidzinski *et al* 2012, Dislich *et al* 2017), reflecting the trend in primary research identified in our study. Our study has shown that reviews calling for further research on the biodiversity effects of oil palm cultivation have largely been satisfied, particularly those with a focus on invertebrate and avian biodiversity (Fitzherbert *et al* 2008, Foster *et al* 2011, Savilaakso *et al* 2014). Other recommendations have not yet been fully addressed. For example, previous reviews have called for research on the implementation and refinement of sustainability standards (Obidzinski *et al* 2012), and the impacts of management practices (Foster *et al* 2011, Savilaakso *et al* 2014, Dislich *et al* 2017), but we have shown there is still a need for research in these areas. Mirroring the bias towards ecological research seen in our study, reviews conducted in the past have also focused on ecological outcomes. A recent paper by Qaim *et al* (2020) reviewed the economic, ecological and social impacts of oil palm expansion, supporting our findings that interdisciplinary research is increasing. Our review has also identified areas for potential meta-analyses. For example, over 50 studies have now been conducted on the effects of cultivation on yield, livelihood, and insect and bird biodiversity, showing a volume of literature appropriate for further analysis. While we have conducted only a quantitative study, the existence of high impact review papers on specific topics, such as the above reviews on the ecological effects of land conversion, indicates that there has been sufficient high quality research completed in order to declare research gaps largely filled. 312 of the sources classified in our paper were not present in the bibliography of any of the six reviews above, showing the value of systematic searching techniques.

5. Conclusions and implications

Our study has identified research areas where there is now abundant data, as well as areas where there are knowledge and synthesis gaps. When examined in the context of trends in oil palm production, sustainable certification priorities, and recognized causes of yield gaps, our findings identified key areas where research effort is lagging behind requirements for the development of more sustainable and productive oil palm. When measured against country production capacity, we found that research context generally followed production trends. However, several high producing countries were notably absent, and greater attention is needed for regions outside of Southeast Asia which are expected to be the locations of future growth. Over 10% of the world's agricultural land is devoted to oil palm, but there is great heterogeneity in plantation structure and management (Comte *et al* 2012). This variability has effects on production capabilities, ecological sustainability, and worker conditions. While studies on the influences of these factors have been called for in previous reviews (Foster *et al* 2011, Savilaakso *et al* 2014, Dislich *et al* 2017), we have shown there is still a significant knowledge gap. Research gaps are most pressing on the effects of mono- versus poly-culture systems, and the effects of management interventions on ecosystem services other than yield. Finding more sustainable options within these management interventions has great potential to bring both ecological and social benefits. We have also identified several differences in scope and context between ecologically and socially focused research, which may prove a challenge to interdisciplinary efforts to bring these findings together and identify holistic practices for more sustainable palm oil production. For example, social outcomes were most commonly measured in smallholder plantations, whereas ecological outcomes were more common in industrial plantations. A solution may be to increase research on plasma farms, which are owned by smallholders but linked to a larger company.

Interdisciplinary research is often more complex, and therefore more challenging, than traditional research. Common difficulties include identifying relevant funding, communication and work-culture differences between disciplines, and methodologies which are difficult to merge (Bromham *et al* 2016). However, if sufficient funding and time is available, respect and understanding between disciplinary representatives can achieve true integration and valuable research (Bennett *et al* 2017). Of course, interdisciplinary research does not guarantee an immediate solution to the socio-ecological issues of oil palm cultivation, but may offer a more inclusive and nuanced understanding of current issues and potential resource management. Given the multiple knowledge gaps identified in this study, we suggest that research priority should be given to topics with tangible benefits for management or wellbeing. This includes research that can inform management choices to benefit both social and ecological outcomes, such as intercropping with consumable crops to help smallholders avoid nutritional deficits, while also creating a more diverse habitat for pollinators. We hope that the gaps identified by this study will provide a framework for researchers working in relevant disciplines to identify future key research topics.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no competing interests.

Author contribution statement

V R W designed the study, carried out the searches and classification sorting, conducted data analysis, and worked on writing of the manuscript. S L worked on the study design and writing of the manuscript throughout all stages. J S was the second reviewer for the inter-reviewer consistency check at the exclusion and classification stage and provided comments on the manuscript. G S advised on the study design and provided comments on the manuscript. E T worked on the study design and writing of the manuscript throughout all stages. All authors read and approved the final manuscript.

ORCID iDs

Valentine Joy Reiss-Woolever
https://orcid.org/0000-0002-6905-4387

Sarah Helen Luke https://orcid.org/0000-0002-8335-5960
Jake Stone https://orcid.org/0000-0003-2151-4353
Gorm Eirik Shackelford https://orcid.org/0000-0003-0949-0934
Edgar Clive Turner https://orcid.org/0000-0003-2715-2234

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