

## RESEARCH ARTICLE

# A systematic map of within-plantation oil palm management practices reveals a rapidly growing but patchy evidence base

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## Abstract

Although oil palm expansion has had severe environmental impacts, oil palm also has the highest yield per hectare of any vegetable oil crop. Compared to many other crops, it has the potential to support high complexity habitats, with minimal chemical input, and relatively high levels of biodiversity and ecosystem functioning. However, there has been little synthesis of available research on oil palm management strategies to support delivery of more sustainable cultivation. In this paper, we provide a systematic map compiling all available evidence assessing within-plantation oil palm management practices at the cultivation stage, with a focus on practices that affect biodiversity and environmental processes. Using approaches adapted from systematic review protocols, we catalogued oil palm management publications to provide details of geographic location, year, interventions tested (i.e. agricultural practices), targeted outcomes of interventions, co-occurrences between different interventions and outcomes (including multiple outcomes), and study design. Most studies were conducted in Southeast Asia, with fewer studies conducted in South America or Africa. Twenty-six interventions were observed in the literature, across six categories: soil, understory, within-crop, landscape-level, replanting, and mixed/multiple interventions. The most common interventions tested were landscape-scale interventions, such as maintaining forest fragments/buffer zones, whereas interventions involved in replanting were the least researched. Eight outcomes were considered: soil fertility, soil erosion, water quality and availability, pest control, replanting, maintenance of biodiversity and areas of high conservation value, and reducing air pollution and greenhouse gas emissions. Studies researching biodiversity were the most common, whereas comparatively few studies considered replanting and reducing emissions. Most primary studies were observational, with experimental studies being rarer, especially in biodiversity research. We match our findings to the Roundtable on Sustainable Palm Oil's environmental sustainability criteria to illustrate how policy-makers and producers may use our map to access evidence supporting cultivation-stage oil palm sustainability management. This study provides valuable information to inform best management practices and direction for necessary future research.

## OPEN ACCESS

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## Author summary

Oil palm agricultural expansion has been identified as a driver of deforestation, biodiversity loss, and greenhouse gas emissions. However, once established, the long-term impacts of oil palm agriculture on the environment can be mitigated through the implementation of sustainable agricultural practices that maximize agricultural yields while minimizing environmental damage. Here, we summarise the status and extent of current oil palm agriculture research to highlight which within-plantation agricultural practices (i.e. interventions) have been researched and/or experimentally tested, as well as the ecological outcomes of these interventions, and how and where these have been studied. We also connect each research study to environmental sustainability criteria established by the Roundtable on Sustainable Palm Oil (RSPO), a global non-profit that develops voluntary social and environmental criteria that plantations must meet to produce the highest certification standard for oil palm cultivation. Our review facilitates access to current research on oil palm management practices by cataloguing each study by intervention, outcome, study method, study region, and associated RSPO sustainability criteria. We also identify interventions and outcomes that have received the most research attention, and areas where there are gaps in research.

## Introduction

### Potential for more sustainable management of oil palm

There are substantial environmental concerns associated with the oil palm industry and its expansion, including deforestation, habitat fragmentation, biodiversity loss, and greenhouse gas (GHG) emissions [1–3], and it is clear that remaining forest habitats must be protected to conserve tropical biodiversity. However, once established, oil palm also has the highest yield per hectare of any vegetable oil crop [4] and therefore has the potential to meet global demands for vegetable oil while minimizing the land required for production. Oil palm plantations can also foster higher structural complexity than many other alternative vegetable oil crops, and therefore have greater opportunity to support biodiversity. High structural complexity is created because palms are perennial and long-lived, and exhibit a low level of disturbance during manual harvesting of fruit bunches [5]. Fruit can be harvested for 25 years without the need for annual replanting, heavy machinery, or converting new land for cultivation, thus allowing for continuous growth [5]. Taller palms have a closed canopy which buffers microclimatic conditions in the understory [6]. In addition, deeper leaf litter and higher epiphyte abundance in more mature plantations may provide increased habitat complexity to support a wider diversity of species compared to newly-planted plantations [6]. Heterogeneity in oil palm plantation understory vegetation may increase beneficial chemical and physical soil properties [7], and mature palm leaf litter may increase soil fertility, further reducing the need for chemical inputs [8]. These features of the oil palm plantation environment mean that there is substantial scope to manipulate environmental complexity to support higher species diversity and related ecosystem services [6,9,10], including services that support ecosystem functions and crop productivity [11] as well as potentially reducing the need for chemical fertilizers [12] and pesticides [13]. Additionally, oil palm requires fewer fertilizer inputs compared to many other crops, and it grows in a variety of tropical soils with relatively few requirements for specific chemical and physical soil properties [14].

Oil palm's potential for greater environmental sustainability may be enhanced through the implementation of agricultural practices that provide high yields while minimizing the negative environmental impacts of ongoing production. Practices that have been suggested include planting improved cultivars with higher yield per palm [15,16], optimizing application of organic and other fertilizers through leaf and soil analysis [17,18], and controlling harvest timing for oil palm fruit bunch ripeness and quality to maximize oil extraction rates [19]. In addition, the use of various types of forest or riparian buffers can regulate soil erosion and maintain biodiversity without causing negative impacts on plantation longevity, yield, or production-relevant ecosystem functions [20–22]. Other practices include the use of environmentally-friendly pesticides, the biological control of weeds and pests, and planting cover crops to increase soil fertility, among others (see for e.g. those listed in [23–25]). Additionally, precision agriculture approaches can use interactive, computer-oriented technological systems to gather site-specific data and/or modeling data, which can be used to monitor, analyze, or predict the effectiveness of different agricultural management interventions [26]. These technologies, specifically remote sensing, are increasingly being used to gather data on existing oil palm plantations, including information on geographic distribution and estimated yield, or to detect potential sites suitable for future conversion to oil palm [27].

### Oil palm sustainability schemes

To reduce the negative impacts of oil palm cultivation on the environment and to improve the wellbeing of oil palm workers, several oil palm sustainability certification schemes have been developed by both government-led and not-for-profit initiatives. These schemes outline criteria that must be met to achieve certification within each scheme's framework. These, in turn, ensure compliance with government regulations and allow price premiums and access to a larger potential market, as consumers become increasingly sustainability-conscious in their purchasing choices [28]. Three major oil palm sustainability certification schemes include the Malaysian Sustainable Palm Oil (MSPO), the Indonesian Sustainable Palm Oil (ISPO), and the Roundtable on Sustainable Palm Oil (RSPO). The MSPO and the ISPO are two examples of government-led certification schemes that detail legally required standards for within-country oil palm cultivation and are mandatory criteria for large oil palm plantations in Malaysia and Indonesia, respectively [29,30]. In contrast, the RSPO is a global, multi-stakeholder non-governmental non-profit organization that develops voluntary social and environmental criteria that plantations must meet to produce RSPO Certified Sustainable Palm Oil (CSPO), the highest certification standard for oil palm cultivation [31].

RSPO criteria are designed to fulfil seven social and environmental principles, termed the RSPO Principles & Criteria (P&C) [25]. The RSPO P&C Principle 7 (“Protect, conserve and enhance ecosystems and the environment”) includes all criteria on land use, planting, and cultivation using environmentally sustainable agricultural practices. The RSPO provides oil palm producers with information to achieve its criteria, including several ‘Manuals on Best Management Practices’ (BMP) for different planting areas, including cultivation within peatland and management of riparian areas [20,32]. The RSPO's P&C outcomes and practices were developed by a multistakeholder Task Force comprised of large plantation representatives and smallholders from Malaysia, Indonesia, and outside Southeast Asia, supply chain representatives and investors, and representatives from environmental and social NGOs. Members of the Task Force determined P&Cs by integrating suggestions from Task Force working groups with feedback gathered from online surveys and public consultation workshops conducted worldwide, alongside their awareness of current research and literature. The RSPO's P&C was most recently revised in 2018, and the assessment and review of the RSPO's P&C is an ongoing

process in which evidence and feedback is evaluated regularly. As such, having easy access to consolidated and summarized current research on oil palm management practices, with guidance on how these practices match to sustainability criteria, would facilitate the integration of evidence into this process.

### Current state of oil palm plantation management research

Primary research studies are needed to inform agricultural management decisions to support sustainable food production, while maintaining or restoring environmental quality [33,34]. While there are many publications on the environmental impacts of converting natural habitats to oil palm (e.g., [1,35–37]) and a growing evidence base related to social impacts [38,39], there are fewer studies researching the ecological impacts of different environmental management practices used within oil palm plantations [37], and to date there has been no review compiling available evidence supporting these management practices. Because of the inherent complexity of tropical agricultural ecosystems, measuring the effectiveness of alternative agricultural management practices can be very difficult [34]. Whole-ecosystem experiments have been recommended as a key approach to study the complex ecological interactions of human-modified tropical forest landscapes, but these types of studies are rare [40]. To develop a strong evidence base that supports agricultural management decision-making, researchers must conduct studies with the least amount of bias, including experimental approaches using controls and randomized study designs that deliver robust and repeatable outcomes [37,41–43].

In this review, we use a systematic mapping approach to quantify trends in published research on within-plantation oil palm management interventions and their environmental outcomes. We focus specifically on environmental impacts, but we acknowledge that social impacts of management interventions and social interactions with management interventions represent key research areas which are outside the scope of the current study. Systematic mapping methodology addresses open-ended research questions by rigorously, transparently, and objectively capturing the extent of evidence that is available related to a specific topic. The available evidence is then described and catalogued to identify knowledge gaps (underrepresented topics in the literature in which further primary research is needed) or knowledge clusters (well-represented topics in primary literature that may benefit from conducting secondary research, such as intervention-specific systematic literature reviews) [44]. Systematic mapping is a quantitative approach to address multi-faceted questions that are inclusive of multiple interventions and outcomes associated with a topic of interest. In our study, we defined “intervention” as any cultivation-stage environmental oil palm management practice conducted within oil palm plantations and “outcome” as any measured effect on biotic/abiotic ecological factors. Our secondary focus was to assess the methodologies applied in these studies, to determine whether well-designed experimental approaches were routinely implemented and, therefore, the likely reliability of results. Specifically, our systematic map addresses the following questions:

1. Which oil palm interventions and outcomes have been studied in which global regions, and how has this changed over time?
2. To what extent have different oil palm interventions and outcomes been investigated through primary research studies and/or secondary research studies, and which of these interventions/outcomes have been explored in tandem?
3. What methodologies and study designs have been used to study different oil palm interventions and outcomes in primary literature (including observational studies, computer modeling/simulation studies, and experimental studies)?

From the findings of our map, we explicitly link study outcomes to RSPO Principle 7 Criteria for environmental sustainability, to identify interventions and outcomes relevant to the environment that have received the most research attention, and areas where there are gaps in research. We also provide a complete reference list of existing evidence to support decision-makers in their management decisions and facilitate knowledge exchange to certification schemes. This evidence is presented in our systematic map table ([S2 File](#)), which includes all oil palm management research studies we identified, as well as the interventions and outcomes addressed by each study.

## Methods

### Systematic mapping approach

We used a systematic mapping approach, adapted from Collaboration for Environmental Evidence (CEE) Systematic Review Guidelines [45], RepORting standards for Systematic Evidence Syntheses (RoSES) Systematic Map Protocols [46], and Cambridge Conservation Evidence Guidelines [47], to collate and catalogue oil palm management publications and provide detailed meta-data for each study. Our stepwise approach included a search of multiple databases and the bibliographies of key publications, removal of duplicate publications, evaluation of relevance at the title and abstract level, and extraction of meta-data at the full text level. A similar mapping method has recently been applied successfully by Tan *et al.*, who used this approach to review studies on the use of expert systems in oil palm management [26].

### Determining the search string

Our search string consisted of three components: defining the subject (oil palm), defining the intervention (inclusive of all within-plantation management strategies at the cultivation stage of oil palm production), and defining the outcome (inclusive of all ecologically-focused outcomes). Before setting the search string for our initial search, we consulted six experts in the oil palm management field to identify ten “benchmark papers” ([S1 Table](#)). Benchmark papers represented exemplar publications in oil palm management research. To set the search string, we reviewed the full text of these benchmark papers to determine core terms commonly used in oil palm management literature. Thirteen core terms were identified that captured the full range of management interventions and their outcomes. Using the Oxford English Dictionary [48] we conducted a search for synonyms and alternative spellings for the core terms, resulting in 76 terms. We then performed a scoping exercise using ISI Web of Science, eliminating terms that yielded less than 1% of relevant articles from the search results. The resulting 12 terms were joined together using Boolean operators—“AND” used to join the three components of the string and “OR” used to join the terms comprising each component: TS = ("oil palm" OR "palm oil" OR "elaeis guineensis") AND TS = (plantation\* OR ecosystem\* OR habitat\* OR agricultur\* OR environment\* OR div\* OR biodiv\*) AND TS = (manag\* OR strat\*). Search results included all benchmark papers, verifying this search string.

### Search sources

An initial literature search was conducted using the online literature data base Web of Science in January 2019. An updated search was conducted in May 2021 using both academic literature and gray literature databases, including Web of Science, Scopus, OpenGrey, Ethos, and British Ecology Society Applied Ecology Resources.

We also conducted a manual search of the references cited in the benchmark papers as well as 10 key review papers in the oil palm field (see [S2 Table](#)), following a “snowball design”, in

which relevant publications from bibliographies were compiled and the citations of these publications were searched for additional relevant works until no new relevant publications were identified [49]. Once duplicate titles were removed, a total of 2,891 papers were retrieved from all our searches, including 1,710 papers accessed via database searches and 1,181 papers accessed through manual snowballing.

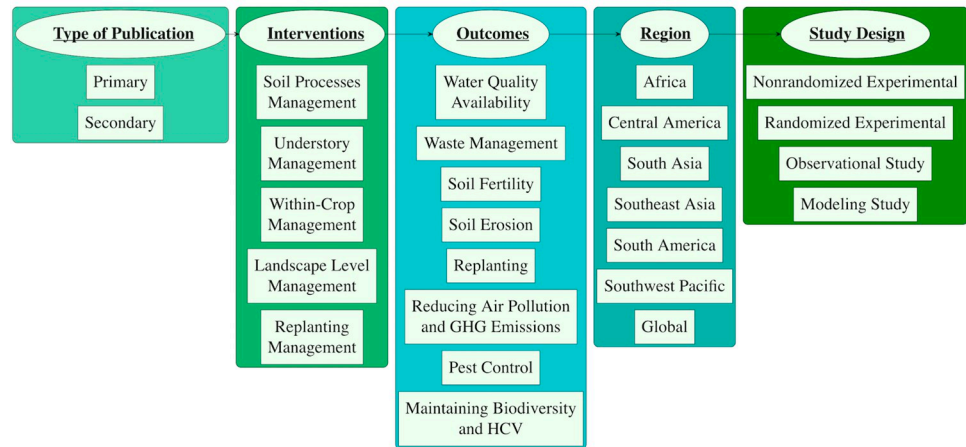
### Inclusion/Exclusion criteria

We assessed the relevance of publications using inclusion/exclusion criteria set using an adapted PICOS review model [50]. In the PICOS model, relevance is determined by examining the following components of a given publication: Population (research subject), Intervention (potential action or management decision studied), Comparator (what comparisons are made), Outcome (the effect of the intervention(s) on the population), and the Study design (the type of research study conducted). To determine relevance, publications were reviewed at the title and abstract-level, and, when additional information was needed, at the full-text level. Publications were considered relevant if they focused on any environmental oil palm management intervention at the cultivation stage of oil palm production, resulting in any outcome affecting biotic/abiotic ecological factors. As we focused on the cultivation stage, our publications were limited to studies that researched interventions and outcomes within established plantations. For this reason, we excluded publications researching selection of land for conversion to oil palm, as well as publications that were just focused on comparing oil palm plantations to other ecosystems. Publications were considered relevant if they compared multiple oil palm sites utilizing different interventions or plantations under two or more differing management systems, even if the study also compared these to other habitats. No date restrictions were applied to the search, and only English publications were considered due to resource constraints. See [S3 Table](#) for full lists of PICOS inclusion/exclusion criteria.

Of the 2,891 papers retrieved, 1,550 publications were excluded at the title-level, 963 publications at the abstract-level, and 8 publications at the full-text level, leaving 370 relevant publications. We provide a completed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist and flow diagram in our supplementary materials (see [S1 Fig](#) for PRISMA diagram, and [S1 File](#) for checklist) [51,52]. PRISMA provides an evidence-based set of items for systematic reviews to report while evaluating the effects of interventions. We also provide detailed information on all publications considered to be relevant to our study, as well as our meta-data classification of these publications in a systematic map table ([S2 File](#)).

### Meta-data classification

Meta-data extracted from the full text of the relevant publications were used to categorize publications based on year published, type of publication, interventions, outcomes, region of study, study methodology, and study design ([Fig 1](#)). Publications were categorized as either primary articles (including original research articles, case studies, and technical notes) or secondary articles (including reviews, commentaries, editorials, and gray literature) [53]. Primary publications were then divided by whether the study directly tested the effectiveness of a specific within-plantation intervention. Studies that tested interventions were further subdivided into categories based on “agroecological practices” (classified by Wezel *et al.* [54], see [S4 Table](#)). Publications that compared plantations engaged in multiple different interventions (including “best management practices” and “industry standard practices”) were not considered to be studies that directly tested specific, individual within-plantation interventions. This is because simultaneous changes in management across multiple interventions makes it challenging to assess the effects of individual interventions. In these cases, publications were



**Fig 1. Flow chart illustrating categories used in meta-data classification.** Meta-data classifications include the following major categories: Type of Publication, Interventions, Outcomes, Region, and Study Design. Relevant sub-categories appear below each major category. At least one or more outcomes were determined for all relevant publications. Primary publications were further categorized by intervention tested, region where the study was conducted, and study design.

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categorized as testing “mixed/multiple” interventions. Secondary publications were not characterized by intervention, as most secondary publications included multiple interventions across different primary studies, targeting one or more outcomes. We chose not to catalogue secondary publications by intervention to avoid inflating the number of publications discussing each intervention, as secondary publications mostly discussed primary studies that were already included within our search and catalogued by intervention.

Primary publications were also categorized by the global region in which the research was conducted. Global region was determined by consulting United Nations’ M49 geoscheme coding classification [55] and identified to the country level whenever possible (S4 Table lists the countries in each global region). While most secondary studies covered multiple regions, secondary publications were categorized by global region whenever possible (we provide this information in our systematic map table, S2 File).

Both primary and secondary publications were categorized by the environmental outcome(s) each study addressed. We identified eight categories representing the most researched outcomes by reading the abstracts of the first 100 relevant publications, ordered alphabetically by first author’s last name and including only one article per author, and discussing prevalent research themes with benchmark panelists and trial screening reviewers (see *Consistency checking*). Environmental outcomes included: soil fertility, soil erosion, water quality and availability, pest control, replanting, maintenance of biodiversity and areas of high conservation value (HCV), and reducing air pollution and GHG emissions. By cross-referencing with RSPO environmental requirement criteria, we also assigned each outcome category to the most relevant RSPO criterion/criteria (S4 Table). Publications were assigned multiple outcome categories when a study researched more than one outcome. The co-occurrences of different outcomes were recorded, as well as the co-occurrences of different interventions and outcomes.

We considered replanting as both an intervention category and an outcome. After 25 years, mature oil palms exhibit reduced oil kernel productivity and reach the end of their “commercial lifespan” [5,56]. For oil palm plantations to remain productive, old palms must therefore be removed and replanted with young oil palms. As an intervention category, replanting management interventions included the management practices involved in all stages of the

replanting process, including practices used to fell palms, remove/clear uprooted palms, and plant new young palms. Because replanting is a multi-stage process, replanting interventions are quite varied, with targeted outcomes that are unique to the stage of replanting. However, these interventions share a common overarching outcome—the successful establishment of young palms. Therefore, we also defined replanting as an outcome, to aggregate all studies that assess interventions at any stage of the replanting process.

As study design can heavily influence the reliability and robustness of research outputs [42], we assessed the quality of the body of evidence in each primary study by categorizing the methodology implemented in the study as observational study, experimental study, or modeling study (S4 Table). If designated an experimental study, the publication was further categorized by study design using the protocol outlined by Christie *et al.* [42]. The study design categories varied in three main components: randomization, sampling before and after the impact (i.e. management intervention) occurs, and the use of a control group [42]. Nonrandomized studies included the following designs: After, which gathers data on an impact group after the impact has occurred; Before-After (BA), which compares data gathered on an impact group before and after the impact; Control-Impact (CI), which compares an impact group and a control group after impact; and Before-After-Control-Impact (BACI), which compares a control group and an impact group both before and after impact. Randomized designs included Randomized Control-Impact (R-CI) and Randomized Before-After-Control-Impact (R-BACI). Randomized study designs are considered the “gold standard” of study designs because they remove any stochastic pre-impact differences to achieve the lowest design bias [42,57,58]. Christie *et al.* [42] found that randomized controlled designs (R-CI and R-BACI) have negligible bias in the datasets they analyzed, whereas controlled designs (BACI and CI) exhibited greater bias, and uncontrolled designs (BA) had the greatest amount of bias.

### Consistency checking

To avoid interpretive bias, three researchers conducted a trial screening of the relevance and outcome classification on 10% of the search results [59]. Reviewers assessed relevance at the title and abstract level. They then categorized relevant publications by outcome(s), by examining the abstract and full text when necessary. Consistency among reviewers was checked using Randolph’s free marginal multirater Kappa, which compares consistency among multiple reviewers selecting multiple, non-mutually exclusive categories [60]. If a discrepancy occurred, the publication was discussed among reviewers until a consensus was determined. Through these discussions, we adapted and clarified the inclusion/exclusion criteria and the eight outcome categories. The Kappa value (K) after screening 158 publications was 0.77, exceeding the guideline of 0.6 [61].

### Data visualization

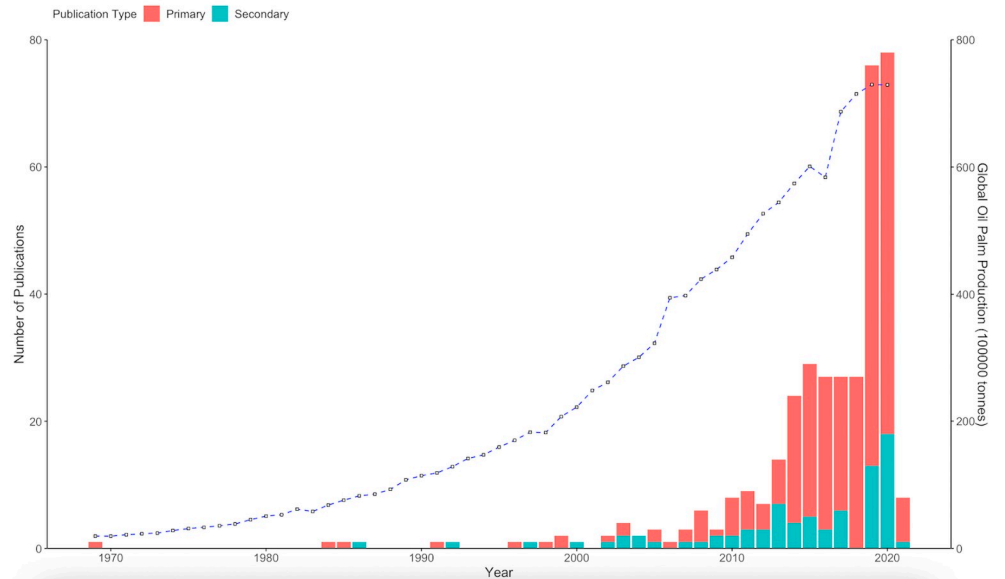
Data visualization was conducted using R [62] and RStudio [63]. The package ggplot2 was used to create all barcharts and heatmaps [64]. Cowplot was used for graph paneling [65], shadowtext was used for within graph text fonts [66], and diagrammeR was used for flowchart construction [67].

## Results

### Distribution of publications over time

A total of 370 relevant publications have been published, with the first appearing in 1969 (Fig 2). After the first publication, there were no relevant publications until 1984. From 1984–2012





**Fig 2. Number of primary and secondary oil palm management publications published annually.** Stacked bars show the number of oil palm management studies published annually, from the first relevant paper published in 1969 until the date of our final literature search in May 2021. Bars are divided into primary and secondary publications. The dotted line shows global annual production of processed palm oil in 100,000 tonnes between 1969 and 2020 [68]. Source: Food and Agriculture Organization of the United Nations. Reproduced with permission from FAO.

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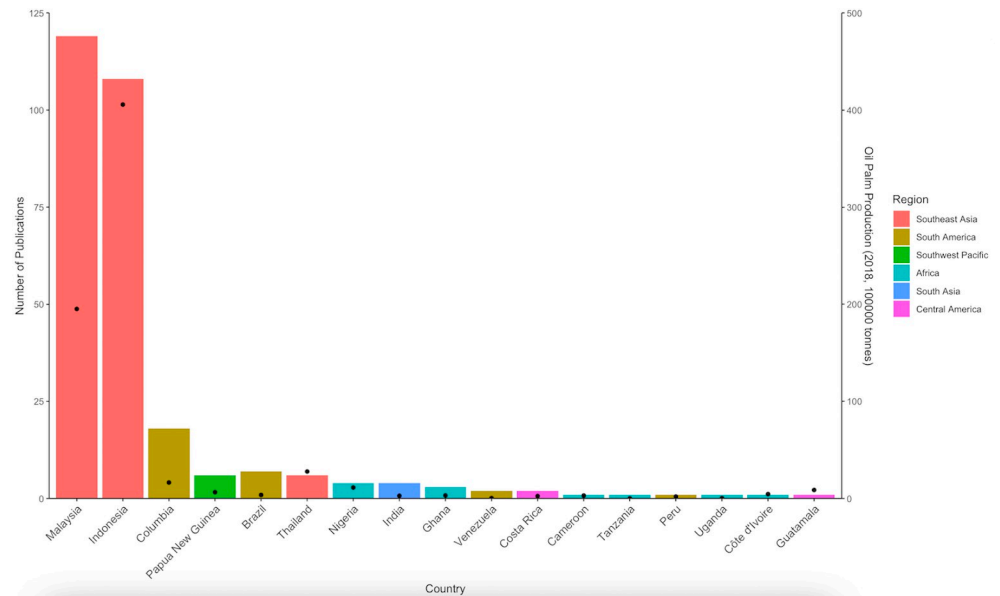
there were a total of 59 publications, with less than 10 relevant publications published per year. This was followed by an increase in publications from 2013–2018 (148 publications), and a rapid increase in publications in 2019–2020, when more than 70 were published per year. Just over 50% of all relevant publications have been published since 2018. Of the total 370 relevant publications, 291 were primary studies and 79 were secondary studies, with the publication of both primary and secondary studies increasing over time.

### Study locations

About 80% of the total primary studies were conducted in Southeast Asia (Fig 3), with nearly all taking place in Malaysia (119 studies) or Indonesia (108 studies). Of the remaining studies, roughly 10% were conducted in South America, with most being based in Columbia (18 studies), or Brazil (7 studies), and 4% in Africa, of which most studies were conducted in Nigeria (4 studies) and Ghana (3 studies). There were also six studies conducted in Papua New Guinea, and four studies in India. Other palm oil producing countries were poorly represented in the literature, with only one or two publications (Cameroon, Venezuela, Costa Rica, Tanzania, Peru, Uganda, Côte d'Ivoire, and Guatemala). There was one study conducted in both Indonesia and Malaysia and one global study, as well as four primary studies using non-site specific, laboratory-generated data. The number of studies generally reflected palm oil production per country (Fig 3), although Malaysia exhibited a higher relative number of publications compared to production than Indonesia.

### Study interventions

We identified 26 specific individual interventions with environmental impacts, which we categorized into five different intervention categories: soil processes management, understory management, within-crop management, landscape level management, and replanting



**Fig 3. Number of primary studies conducted in different countries and global regions.** Bars show the number of primary studies on oil palm management conducted in each country with at least one study from 1969 to 2021. Overlying points indicate each country's total production of processed palm oil in 2018, measured in 100,000 tonnes [69]. Source: Food and Agriculture Organization of the United Nations. Reproduced with permission from FAO.

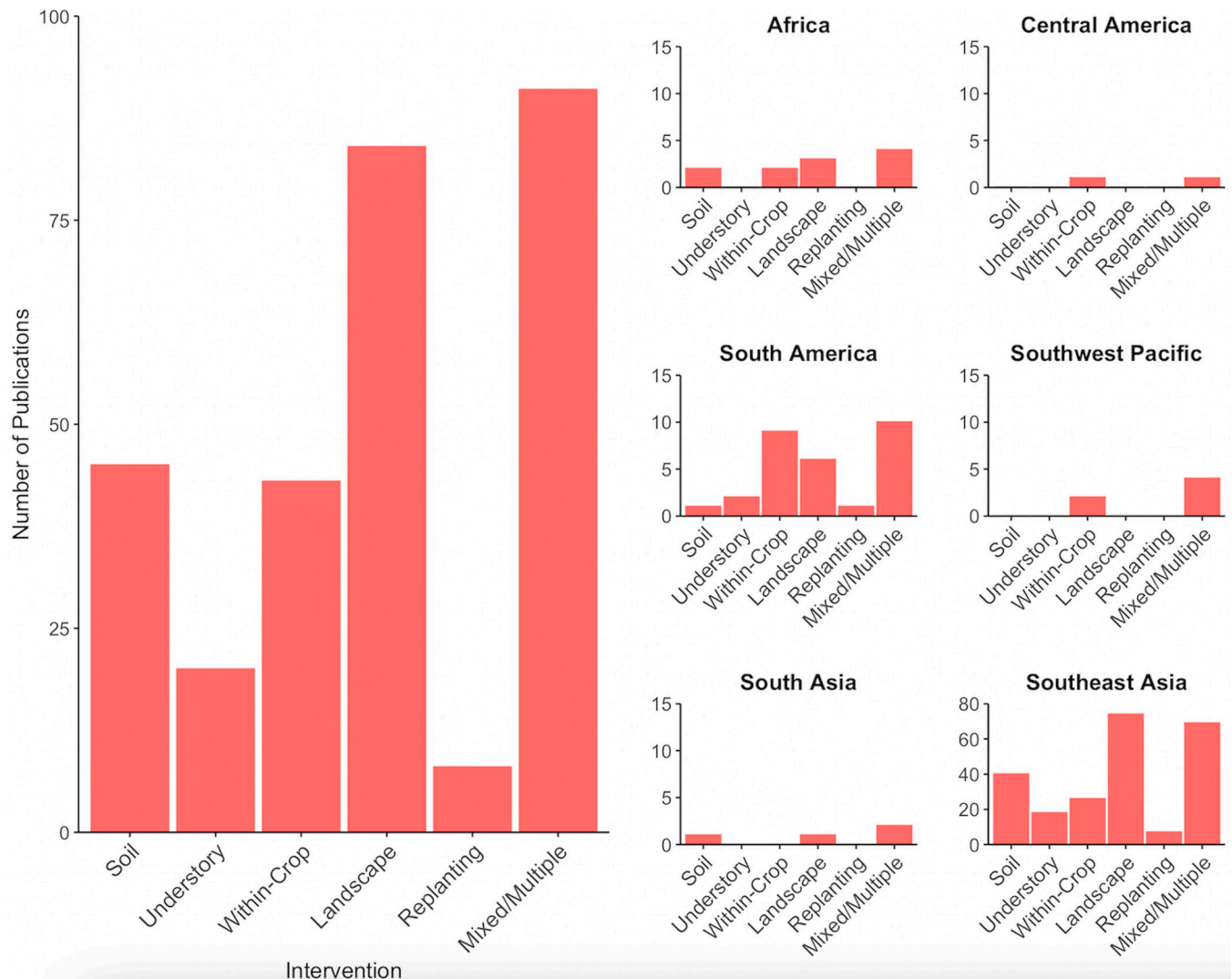
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management (see [S2 File](#) and [S4 Table](#)). The intervention category most researched was landscape level management (about 29% of primary studies, 84 studies) ([Fig 4](#)). In this category, management systems (33 studies) and maintaining and restoring forest fragments/buffer zones (28 studies) were the most tested interventions. Replanting management was the intervention category least represented in the literature, addressed in 3% of primary studies (8 studies). Twelve of the 26 oil palm management interventions found in the literature were investigated in three or fewer studies. Mixed/multiple interventions were researched in 31% of primary studies (91 studies). For each intervention category, the majority of studies were conducted in SE Asia, with the other global regions each contributing ten or fewer studies within each category.

### Study outcomes

The most common environmental outcome studied in primary publications was maintenance of biodiversity and HCV areas (RSPO criterion 7.12), researched in about 44% of primary publications (127 studies) ([Fig 5](#)). The next most studied outcomes were soil fertility (RSPO criteria 7.4 & 7.5) and pest control (RSPO criteria 7.1 & 7.2), researched in 37% (107 studies) and 26% of publications (76 studies), respectively. Reducing air pollution/GHG emissions (RSPO criterion 7.10) was studied in 13% of relevant publications (39 studies), and water quality/availability (RSPO criteria 7.7 & 7.8) in 11% (33 studies). Each of the remaining outcomes were studied in less than 10% of relevant publications: waste management (RSPO criteria 7.3) (7%, 21 studies), soil erosion (RSPO criteria 7.6) (7%, 19 studies), and replanting (RSPO criteria 7.5, 7.6, 7.11) (5%, 14 studies). For each outcome, the majority of studies were conducted in SE Asia, with the other global regions each contributing 11 or fewer studies within each category.

The ratio of primary to secondary studies was highest for publications researching replanting (82% primary studies) and maintenance of biodiversity and HCV areas (82% primary

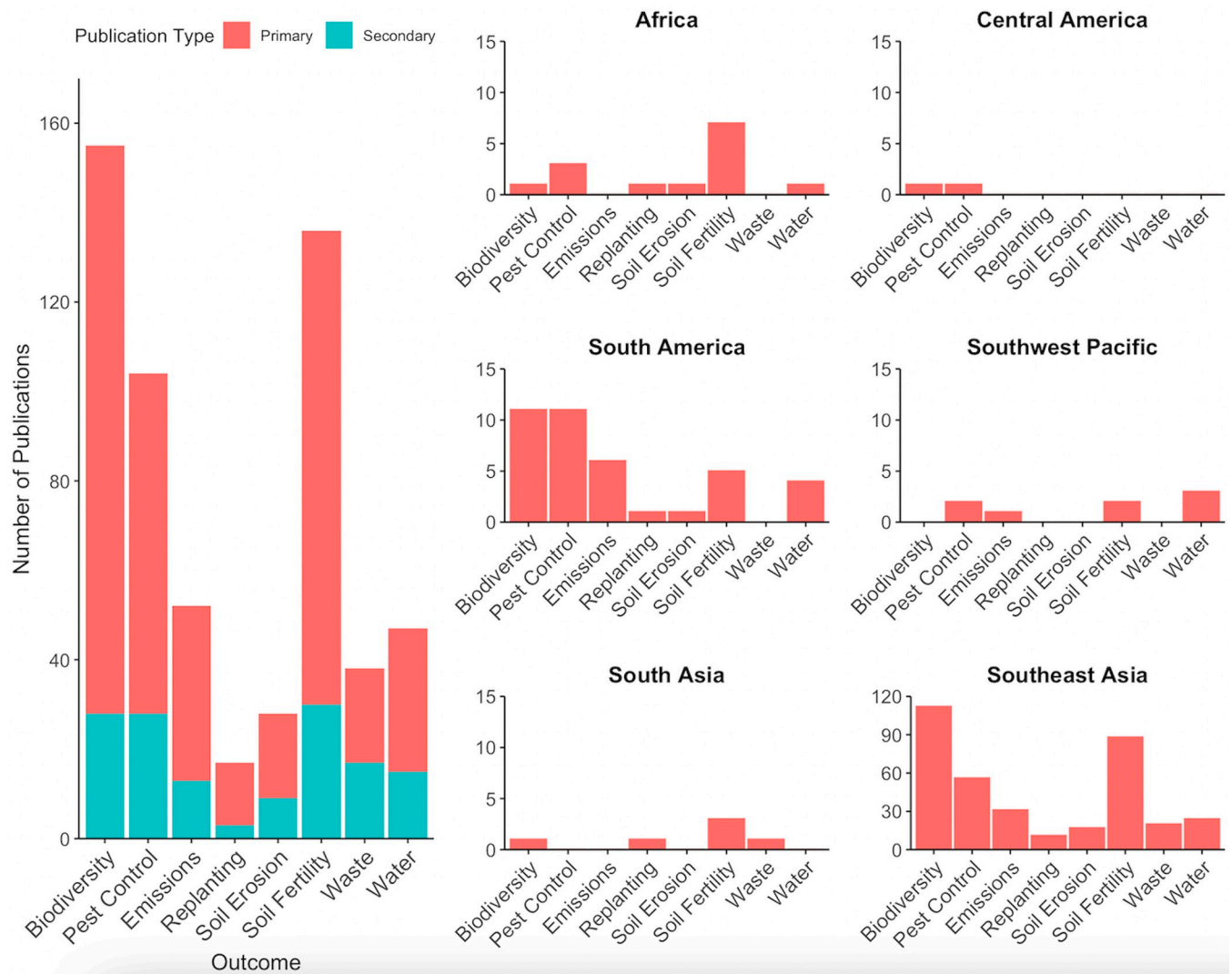


**Fig 4. Number of publications testing intervention categories in each global region.** The graph to the left shows the total number of primary studies testing oil palm management interventions within each intervention category, as well as primary studies that tested multiple specific interventions or mixed, nonspecific interventions within a management system (“mixed/multiple”). Panel graphs to the right show the number of primary studies conducted in different global regions. The axis of the Southeast Asia graph is on a different scale to that of the other global regions, owing to the high number of studies conducted in this region.

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studies) and was lowest for water quality and availability (68% primary studies) and waste management (55% primary studies).

In secondary publications, soil fertility (30 studies), pest control (28 studies) and maintaining biodiversity and HCV (28 studies) were the most researched outcomes, with soil fertility mentioned in around 38% of the secondary literature and both pest control and maintaining biodiversity and HCV mentioned in about 35% of the secondary literature (Fig 5). Waste management (22% of secondary publications, 17 studies), water quality and availability (19%, 15 studies), and reducing air pollution and emissions (16%, 13 studies) were the next most researched outcomes. Soil erosion (11% of publications, 9 studies) and replanting (4%, 3 studies) were the least researched outcomes.

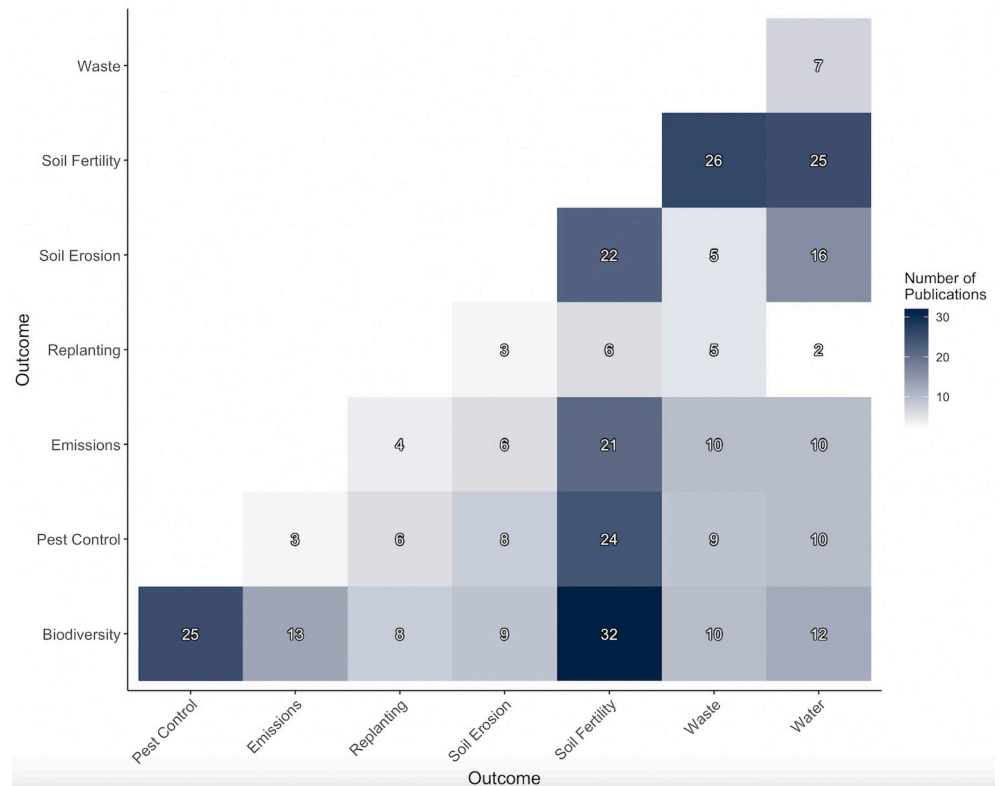


**Fig 5. Number of publications addressing outcomes in each global region.** The stacked bar graph on the left shows the total number of primary and secondary oil palm management studies researching each outcome found in the literature. Panel graphs on the right show number of primary studies researching each outcome in different global regions. The axis of the Southeast Asia graph is on a different scale to that of the other global regions, owing to the high number of studies conducted in this region. Studies researching more than one outcome appear in multiple bars.

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### Co-occurrence of outcomes

Overall, most studies focused on only one environmental outcome (232 studies, 63% of literature base); however, all potential outcome combinations were present in the literature. The most common outcomes explored in tandem were biodiversity and soil fertility (32 studies), biodiversity and pest control (25 studies), waste management and soil fertility (26 studies), water quality and availability and soil fertility (26 studies), and pest control and soil fertility (24 studies) (Fig 6). All publications that studied soil erosion addressed multiple additional outcomes in tandem. More than 90% of publications researching waste management and replanting also addressed additional outcomes. Of the 189 publications focused on maintenance of biodiversity and HCV areas, just over half focused on multiple outcomes (about 56%). Similarly, about 57% of pest control studies focused on multiple outcomes.

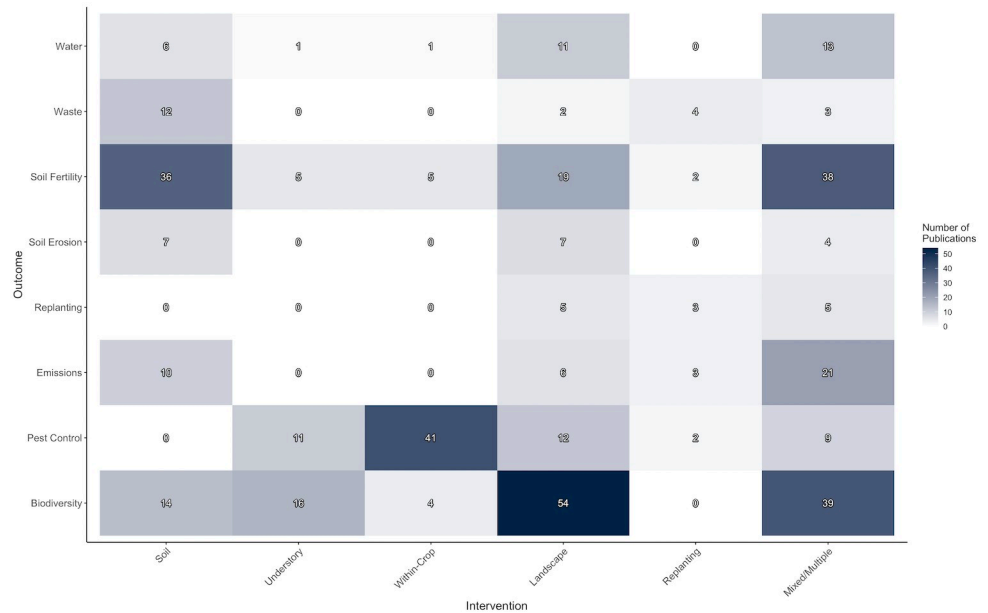


**Fig 6. Co-occurrences of multiple outcomes in relevant primary and secondary oil palm management publications.** The color of each cell represents the number of publications researching each combination of multiple outcomes, with darker colors illustrating higher frequencies of publications, and overlaid numbers indicating the exact number in each case.

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### Co-occurrence of interventions and outcomes

The most common environmental interventions and outcomes explored in tandem were landscape level management with maintaining biodiversity and HCV areas (54 studies) and within-crop management with pest control (41 studies) (Fig 7). Landscape level management was the only intervention category that was researched in tandem with all eight outcomes present in the literature. Understory management interventions and within-crop management interventions co-occurred with the fewest number of different outcomes, as they were both researched in tandem with only four of the eight other outcomes. Not all publications researching replanting management interventions focused on replanting as a primary research outcome. Many studies examined the effects of replanting from outside a replanting context, focusing instead on other outcomes such as waste management, pest control, and reducing air pollution and GHG emissions. These studies assessed replanting interventions without discussing in detail the effects of the interventions on the overall replanting process. Pest control was the most common outcome explored in tandem with a clearly indicated intervention (88% of studies), whereas reducing air pollution and GHG emissions was least commonly researched in tandem with a specific intervention (48% of studies, the rest of the studies researching mixed/multiple interventions). Of the 40 possible intervention-outcome combinations, 13 combinations were not present in the literature.



**Fig 7. Co-occurrences of intervention categories and outcomes researched in relevant primary oil palm management publications.** The color of each cell represents the number of publications researching each intervention-outcome combination, with darker colors illustrating higher frequencies of publications, and the overlaid numbers indicating the exact number in each case.

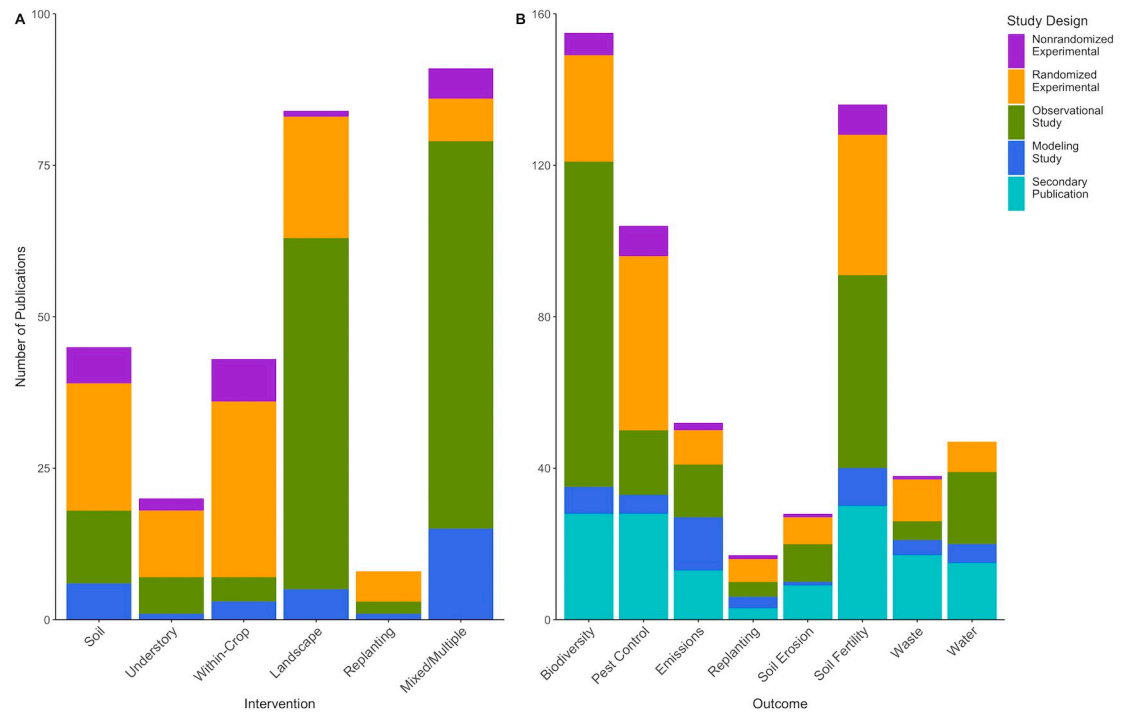
<https://doi.org/10.1371/journal.pstr.0000023.g007>

### Study methodology and design

Most primary studies were observational (50% of primary studies, 146 studies) or experimental (39%, 114 studies), with modeling studies being the least commonly used methodology (11%, 31 studies). For experimental studies, randomized studies were the most common, with R-CI the most common study design (60 studies), followed by R-BACI (33 studies). The next most common study design was BA (11 studies), followed by CI (7 studies), with BACI being the least common study design (3 studies).

Across all specific intervention categories (not including mixed/multiple studies), 43% were randomized experimental studies (86 studies) and 41% were observational studies (82 studies). The least common study designs used were modeling studies and non-randomized experimental designs, both representing about 8% of intervention studies (16 studies for both designs). More than half of the studies researching within-crop interventions, understory interventions, and replanting interventions were randomized studies (Fig 8). Most landscape level intervention studies were observational, with less than a quarter using a randomized experimental design. Within-crop intervention studies showed the highest number of randomized study designs and the lowest number of observational study designs.

The outcome most researched using randomized experimental studies was pest control, and the outcomes in which randomized studies were the least common compared to other methodologies included maintaining biodiversity and HCV areas, water quality and availability, and reducing air pollution and GHG emissions (Fig 8). More than half of the publications researching maintenance of biodiversity and HCV areas were observational studies. Observational studies researching waste management and pest control outcomes were least common. Out of all outcomes, reducing air pollution and GHG emissions had the highest percentage of modeling studies.



**Fig 8. Study designs used in oil palm management publications.** Stacked bars show the number of oil palm management studies researching each intervention (A) and outcome (B), with bars divided by study design. Nonrandomized experimental designs include Before-After (BA), Control-Impact (CI), and Before-After-Control-Impact (BACI). Randomized experimental designs include Randomized Control-Impact (R-CI) and Randomized Before-After-Control-Impact (R-BACI). Axes for each graph are on different scales. In graph B, studies that research more than one outcome appear in multiple outcome bars.

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## Discussion

### Study locations

The regional patterns of publications generally reflect global patterns of palm oil production. Since 1973, Southeast Asia has produced more palm oil annually than any other region [69], and Indonesia and Malaysia currently produce over 85% of the world's palm oil [69,70]. Indonesia and Malaysia's lead in global palm oil production over the last five decades is reflected in the oil palm management literature base: 80% of primary studies were conducted in Southeast Asia, with about half of these studies taking place in Malaysia and half in Indonesia. Although Malaysia's palm oil production has started to level off [69], we found an increase in Malaysian oil palm management studies since 2015. This increase might be due to the introduction of the MSPO as the national standard for oil palm management in 2013, marking a nation-wide drive to systematically certify the industry in Malaysia [71]. In 2017, the Malaysian government announced its plan for MSPO certification to become mandatory for all oil palm producers by 2019 [71]. Likewise, the Indonesian government announced in 2015 that ISPO certification would become mandatory for all Indonesian palm oil producers by 2020 [72]. 2019 saw an even larger increase in oil palm management publications in both Malaysia and Indonesia, which might be the result of an increased push for oil palm sustainability research in both countries related to these initiatives [29,30,73]. Oil palm production has increased in Africa and South America in the past decade [69,74], and we found an increase in studies conducted in these regions in recent years, which may reflect the expansion in these areas [75–77].

While oil palm management research continues to be centered in Southeast Asia, different regions exhibit different environmental and socio-economic conditions that might influence the effectiveness of a given intervention [78]. Environmental factors leading to geographic differences in agricultural production include regional climatic conditions and local soil types. In addition, socio-economic factors such as population density and distance to markets may also lead to regional distinctions [78]. The effects of land-use on tropical biodiversity varies across continents [79], and differences in local biodiversity and the associated ecosystem services species provide may lead to differences in a variety of agroecological factors, including pest control and soil fertility [11]. Future research should, therefore, prioritize region-specific intervention studies, as the results of studies conducted in one area might not be applicable to another region.

### **Trends in intervention-testing studies and their targeted outcomes**

The impacts of specific interventions on pest control was the most commonly researched environmental intervention-outcome combination. Integrated pest management (IPM)—the holistic approach to managing pest populations with limited use of chemical pesticides [80]—is a globally-endorsed method of pest control that is mandatory in many countries, and required for RSPO certification [25,81]. The abundance of pest control studies might be due to IPM's longstanding focus on connecting agricultural practices to environmental sustainability outcomes, and the six decades of research on crop protection decision-making [82,83]. Interventions in the landscape level management category were the most researched interventions in the literature and have been conducted in tandem with all eight management outcomes identified. The larger scope of outcomes targeted by this category might be because this category included the most diverse range of interventions. Additionally, landscape-level interventions are often larger-scale, ecosystem-wide approaches that engage in system-wide practices to address multiple outcomes in tandem (see, for example, the multiple ecological functions addressed in agroforestry interventions [84,85]), making it more likely that a wider range of outcomes are addressed.

Most other intervention categories were explored in fewer studies and in tandem with fewer outcomes. While not all combinations of outcomes and interventions have high priority for oil palm sustainability research, our map indicates several important gaps in the literature base, indicating key areas for future research. For example, no soil processes interventions were tested for pest control outcomes, and few were tested for maintaining biodiversity and HCV areas. Studies have indicated that biodiverse soil communities are important to soil health, which in turn affects plant defense against pests [86–88], making the intersection between soil processes and these two outcomes a fruitful area for future work. No within-crop management interventions were tested for reducing soil erosion. Future research should explore interventions such as intercropping, which has been shown to reduce soil erosion in other agricultural crops, such as potatoes, millet, and cassava (see for example [89–92]). Likewise, no understory management interventions have been tested to reduce soil erosion, although interventions at this level have proven effective in other tree plantation landscapes, such as pine and teak trees (see for example, [93,94]). Future research should determine the effects of different understory cover levels on soil erosion in oil palm landscapes (see for example, the protocols outlined in [34]).

### **Trends in multiple outcome studies**

Our map indicates that all possible environmental outcome combinations were present in the literature, although some outcome combinations were more researched than others. For



example, multiple outcomes were common in studies researching soil erosion and waste management. These studies often addressed outcomes that have clear ecological interactions. For example, studies of soil erosion commonly addressed soil fertility and water quality, as these are all factors associated with soil health [95]. Likewise, waste management was often studied alongside soil fertility and maintaining biodiversity, as there are well-established connections between recycling of oil palm waste products (such as cut fronds and empty fruit bunches), soil nutrients, and soil bacterial and insect biodiversity [96,97].

As agricultural systems are ecologically complex, with many interconnected components, studies that address multiple outcomes simultaneously could provide a more in-depth ecosystem-wide analysis of the system than those that consider only one outcome [98,99]. Weighing the impacts an intervention has on different outcomes can reveal whether the intervention provides benefits to the entire agricultural system, or whether the intervention provides potential benefits for one outcome yet leads to negative impacts on other outcomes. While the ecological links between some outcomes are less apparent and/or critical to sustainable management decisions, our map shows that there are clear gaps in inter-outcome research that should be prioritized in future research. IPM, for example, integrates multiple natural control agents by managing the agricultural landscape at the ecosystem-level, and multi-faceted research is critical to understanding and refining this approach [83,100]. In addition to ecological considerations, determining the effects of a single intervention on multiple outcomes may also lead to a reduction in costs and labor. Implementing a single intervention that achieves multiple desired outcomes may be cheaper and more efficient than implementing multiple interventions, through savings in plantation management costs [72].

We found that a low percentage of pest control studies focused on multiple outcomes, even though pest control was the third-most researched outcome in primary studies. Future pest control studies should address multiple outcomes in tandem because IPM methods may affect diverse ecosystem functions, including soil fertility [101,102], biodiversity [103–105], and water quality [106,107]. Biodiversity is also likely to have strong influences on other outcomes. For example, in other agricultural systems, biodiversity has been linked to many outcomes, including reducing GHG emissions [108] and improving water quality and soil fertility [109]. While maintaining biodiversity and HCV areas was the most researched outcome in primary studies, fewer than half of these studies focused on more than one outcome. Future biodiversity studies should focus on multiple outcomes, as biodiversity is a key component of many diverse ecological processes important to ecosystem functioning [110–112] and an ecosystem's overall resilience [113,114].

### Few studies address GHG emissions

Studies researching specific interventions for reducing air pollution and GHG emissions were rarely found in the literature. Given the current state of climate change and its expected future impacts as well as the impact that agricultural production has on GHG emissions [115], future research should prioritize testing cultivation-stage interventions that reduce air pollution and GHG emissions. Although GHG emissions are much higher during the conversion of forest to plantation than at the cultivation stage of oil palm [116], GHG emissions at the cultivation stage are still not negligible and vary according to several factors, including land-use history and age of palms [117–119]. Additionally, oil palm emissions have been shown to vary based on interventions applied, including choice of fertilizer, replanting timing, and palm variety [118,120]. Given the threat that climate change poses to food security and the economies and livelihoods that depend on agriculture [121], and because cultivation stage management choices play a considerable role in determining a plantation's GHG emissions, we suggest that

future research should prioritize assessing emissions associated with common sustainability interventions. Modeling studies could also be conducted to assess the effectiveness of interventions under alternative climate change scenarios, as these may be expected to vary with changing climatic conditions (see for example [122,123]). Linked to this, it is also important to consider how different management strategies would perform under changing climatic conditions. For example, interventions that reduce soil erosion may be likely to be relatively more important in areas where extreme rainfall events increase in severity as a result of climate change (see for example [124,125]).

### **Replanting studies: Few studies support current replanting plans**

Interventions and outcomes associated with replanting management were the least commonly explored interventions/outcomes in the literature base. Future research should prioritize replanting research, as market demands for palm oil are increasingly being met through the replanting of existing plantations [77,126]. This is because many plantations were established during the first major expansion of the oil palm industry in the 1990s [68], and are now reaching the end of their 25–30 year commercial lifespan. In Indonesia alone, 500000 ha of oil palm plantations will be replanted by 2022 [127]. In addition, fewer new plantations are being established in Malaysia and Indonesia following the rollout of MSPO and ISPO certification schemes, which both place limitations on the conversion of forest and natural landscapes to oil palm plantations [128]. While replanting pre-existing plantations is far less environmentally damaging than converting forests, replanting can still lead to detrimental environmental effects, including biodiversity loss [129] and the disruption of soil and hydrological systems [56,130]. In particular, replanting on areas of peat soil can lead to damage to peat [131] and high GHG emissions and air pollution [132]. The development of practices to reduce the negative impact of replanting on biodiversity and ecosystem functioning while maintaining yield has been noted as a high priority area in oil palm management and research [133]. Future research should prioritize replanting intervention studies that address multiple outcomes related to ecosystem functioning.

### **Study designs for oil palm management decision-making**

Most primary studies were observational, with only 39% using experimental study designs. Observational studies were the most common designs used to research biodiversity outcomes. In general, observational studies are common in biodiversity conservation research [42], although these approaches have been criticized as lacking robustness [41,42,134]. Testing the effectiveness of interventions using controlled, randomized experimental designs would provide clearer management recommendations to achieve beneficial levels of biodiversity [41,42,135]. While observational studies can provide correlational information on environmental heterogeneity in different sites, experimental approaches can be designed to control for variation in environmental conditions which would otherwise obscure relationships between variables of interest [136]. Observational studies were also the most common design used to assess landscape management interventions, perhaps because landscape-wide experimental approaches can be expensive and challenging to implement [137]. Large-scale experimental approaches may be the most successful methods to assess the impact of landscape-level interventions; interventions at this level affect multiple ecosystem functions across the entire agricultural landscape, and experimental approaches can be used to control for environmental variation [136]. In contrast, pest control was the outcome commonly researched in randomized experimental studies. This may be because of the field's historical use of laboratory-based

research and focus on technical or technological studies [83], in which experimental approaches may be more common.

### Evidence and gaps in evidence supporting sustainability criteria

Some priority areas identified by oil palm environmental sustainability certification schemes, including those identified by RSPO P&C, have received far more primary and secondary research attention than others. The systematic map table (S2 File) provides information on which RSPO environmental criteria have been well-researched within the literature base. For example, most primary studies focused on maintaining biodiversity and HCV areas as an outcome, presenting an extensive research base to support RSPO criteria 7.12. Many of these biodiversity studies were observational, however, so additional experimental studies may be needed to provide more robust evidence to support RSPO criteria 7.12. There is a strong evidence base comprised of experimental studies to support criteria 7.4–7.5 on soil fertility and 7.1–7.2 on pest control. Soil fertility, pest control, and maintaining biodiversity and HCV areas were also the most prevalent outcomes addressed by secondary publications. The remaining five outcomes (linked to 8 different RSPO criteria) were considerably less represented in the literature base in both primary and secondary publications. Additional primary studies should be conducted to help support environmental sustainability schemes in the following areas: reducing air pollution and GHG emissions (RSPO criteria 7.10), water quality/availability (RSPO criteria 7.7 & 7.8), waste management (RSPO criteria 7.3), soil erosion (RSPO criteria 7.6), and replanting (RSPO criteria 7.5, 7.6, 7.11).

To provide the RSPO and other sustainability frameworks with an accessible, more complete perspective of oil palm sustainability evidence, future work should prioritize conducting reviews on the evidence supporting these other environmental oil palm sustainability outcomes, as well as multidisciplinary reviews that synthesize research on multiple outcomes. Such secondary studies are key to developing evidence syntheses that aggregate primary research studies and identify evidence for policy and management decisions [44]. Our systematic map table (S2 File) indicates secondary studies that can provide certification organizations such as the RSPO, policy makers, and producers with accessible information on the evidence syntheses related to these well-researched outcomes. Additionally, white papers, executive summaries, and other synopses could frame the findings of secondary studies in ways that are more accessible to different audiences, such as governmental organizations and non-profit organizations. These synopses benefit decision-makers by improving access to scientific information and eliminating the need to sift through the literature base directly [138,139].

### Limitations and priorities for future assessment

This study was limited to English-language publications and is therefore missing publications in other languages. The scope of the assessment that we could address in a single paper was necessarily also limited. We chose to focus on changing environmental management practices and environmental outcomes within the cultivation stage of palm oil production, as this has substantial potential to increase environmental sustainability of the crop [6,9–13]. This complements a recent systematic map of research studies on precision agriculture and expert systems in oil palm plantations completed by Tan *et al.*, which focused on strategies for collecting data within plantations [26]. To develop our understanding further, it would be valuable to consider sustainability interventions and outcomes at other stages of the palm oil production process. In particular, future studies on environmental interventions and outcomes could map research conducted at the pre-cultivation stage, in which sites are selected and prepared for planting [5], and the post-cultivation stage, in which palm oil is extracted from fruits,

processed, and prepared for distribution [5,140]. Mapping these stages would allow the synthesis of evidence to identify the most sustainable practices at all points in the production pipeline. It would also allow certification organizations such as the RSPO to identify priority research areas as well as areas of overlap, in which the interventions and outcomes of one stage can support those of another. For example, post-cultivation stage wastes such as empty fruit bunches and palm oil mill effluent (POME) can be used as organic fertilizer at the cultivation-stage [141,142].

Conducting an additional systematic map that investigates the available literature base for social sustainability guidelines would also be highly beneficial. Oil palm agriculture can reduce poverty in regions with few land development options and can help improve smallholder livelihoods [143,144], but issues such as land conflict, social inequity, and declines in village wellbeing can also be common [144], and smallholders can face challenges such as lack of market access, educational resources, and poor credit and financial resources [145]. In addition, workers in larger plantations can face unsafe working conditions, wage insecurity, and lack of access to education and job training [146]. It is therefore important that possible interventions to improve social sustainability are tested, and the current evidence base for this should be assessed in order to help direct future research. It is also critical that additional interdisciplinary socio-ecological research is conducted to assess the social impacts of environmental management interventions alongside their ecological impacts [39]. Finally, it is important to conduct research to assess how social factors may influence the uptake, implementation, and impacts of environmental management practices. For example, interventions recommended to improve agricultural sustainability and resilience to climate change can be slow to be implemented by farmers, due to constraints in financial resources, access to education, information, and technical skills [147], illustrating the interconnection between environmental and social factors. Identification of strategies to facilitate uptake of more environmentally sustainable practices are therefore also important. For example, a field school teaching climate smart farming practices in the Philippines was able to increase uptake of climate smart farming strategies [148].

## Conclusions

This is the first extensive systematic map of within-plantation oil palm management literature that directly links study environmental outcomes and interventions to sustainability criteria, providing a summary of the current evidence base to inform the development of more sustainable oil palm management practices. This evidence base will be useful for certification organizations, policy makers, and palm oil producers by illustrating which environmental outcomes and interventions have been experimentally tested as effective methods to achieve environmental sustainability in oil palm cultivation. It will also assist researchers in prioritizing where to direct their future work. In our systematic map table (S2 File) we have linked publications to the RSPO criteria as an example to guide oil palm producers in their decision-making process. To continue developing the knowledge base, we suggest that the key knowledge gaps identified in this systematic map should become the focus of further study by oil palm researchers. These include studies testing the environmental effects of replanting interventions on multiple outcomes, studies testing interventions to reduce air pollution and GHG emissions at the cultivation stage, interdisciplinary studies testing the impact of single interventions on multiple outcomes, and management system studies exploring how multiple interventions can be implemented to maximize their effectiveness. Future oil palm research should aim to test the effectiveness of specific interventions to achieve clearly indicated outcomes by implementing effective study designs with the least design bias possible, such as randomized,

controlled experimental designs. Our findings also show that the majority of oil palm research is conducted in Southeast Asia. To provide additional insight into environmental sustainability in oil palm landscapes globally, we suggest that future studies take place in palm oil producing countries within Africa, South America, a wider range of countries in Southeast Asia, as well as countries such as Papua New Guinea and India. These studies will provide further information on differences in local ecology and the effectiveness of interventions in different global regions. We also encourage future investigation of the current evidence base on potential management options to foster increased social sustainability, as well as similar investigations to increase the understanding of interactions between environmental and social factors towards developing more-sustainable oil palm management practices.

## Supporting information

**S1 Table. Benchmark publications selected by a panel of six experts in the oil palm environmental management field\*.** These papers were used to determine and confirm the search string and were also used to conduct the manual “snowball design” literature search.

(TIFF)

**S2 Table. Exemplar publications in oil palm cultivation interdisciplinary research.** These papers were used to conduct manual “snowball design” literature search.

(TIFF)

**S3 Table. PICOS model inclusion/exclusion criteria to assess publication relevance.**

(PNG)

**S4 Table. Meta-data classifications used to catalogue oil palm management publications.**

(PDF)

**S1 File. PRISMA Checklist.**

(DOC)

**S2 File. Systematic Map Table.**

(XLSX)

**S1 Fig. PRISMA Flow Diagram.**

(PNG)

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