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The socioecological benefits and consequences of oil palm cultivation in its native range: The Sustainable Oil Palm in West Africa (SOPWA) Project

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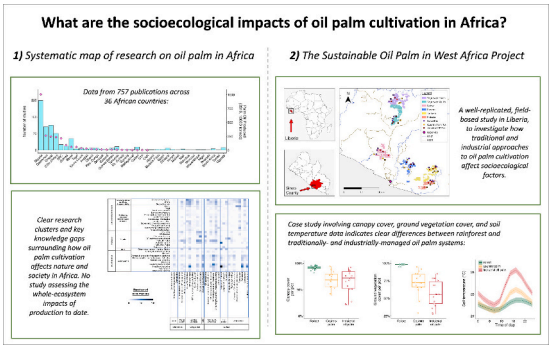
HIGHLIGHTS

- Oil palm is a globally important crop but cultivation in Africa is understudied.
- We use systematic mapping and a new programme—the SOPWA Project—to fill this gap.
- Our mapping reveals no studies on the whole-ecosystem impacts of African oil palm cultivation.
- SOPWA data suggest traditionally- and industrially-managed oil palm impacts whole-ecosystems.
- Future SOPWA work will investigate oil palm impacts across taxa and functions

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture is expanding rapidly across the tropics. While cultivation can boost socioeconomic conditions and food security, it also threatens native ecosystems. Oil palm (*Elaeis guineensis*), which is grown pantropically, is the most productive vegetable oil crop worldwide. The impacts of oil palm cultivation have been studied extensively in Southeast Asia and – to a lesser extent – in Latin America but, in comparison, very little is known about its impacts in Africa: oil palm's native range, and where cultivation is expanding rapidly. In this paper, we introduce a large-scale research programme – the Sustainable Oil Palm in West Africa (SOPWA) Project – that is evaluating the relative ecological impacts of oil palm cultivation under traditional (i.e., by local people) and industrial (i.e., by a large-scale corporation) management in Liberia. Our paper is twofold in focus. First, we use systematic mapping to appraise the literature on oil palm research in an African context, assessing the geographic and disciplinary focus of existing research. We found 757 publications occurring in 36 African countries. Studies tended to focus on the impacts of palm oil consumption on human health and wellbeing. We found no research that has evaluated the whole-ecosystem (i.e., multiple taxa and ecosystem functions) impacts of oil palm cultivation in Africa, a knowledge gap which the SOPWA Project directly addresses. Second, we describe the SOPWA Project's study design and—using canopy cover, ground vegetation cover, and soil temperature data as a case study—demonstrate its utility for assessing differences between areas of rainforest and oil palm agriculture. We outline the socioecological data collected by the SOPWA Project to date and describe the potential for future research, to encourage new collaborations and additional similar projects of its kind in West Africa. Increased research in Africa is needed urgently to understand the combined ecological and sociocultural impacts of oil palm and other agriculture in this unique region. This will help to ensure long-term sustainability of the oil palm industry—and, indeed, all tropical agricultural activity—in Africa.

1. Introduction

Agriculture is a dominant ecosystem globally (Ramankutty et al., 2018; Song et al., 2018); in 2023, farmland and pastureland occupied nearly 50 % (about 48 million km^2) of habitable terrestrial land (Ritchie and Roser, 2021). Since the early 2000s, rates of global agricultural expansion have fallen, but agriculture is still expanding rapidly in the tropics (Ramankutty et al., 2018; Song et al., 2018). Expansion of tropical agriculture has been driven by a growing human population, increases in per capita consumption rates for agricultural-derived resources, and the high economic value of agriculture in many tropical countries (Curtis et al., 2018; Ramankutty et al., 2018). While tropical agricultural production can increase food security and support human health and livelihoods, conversion of natural tropical habitat to farms and pastures has had severe environmental consequences and changed social dynamics (Drescher et al., 2016; Santika et al., 2020).

In recent years, substantial research activity has aimed to identify strategies to make tropical agriculture more sustainable, i.e., to maintain or increase levels of food production in the long-term while mitigating the ecological and sociocultural impacts of cultivation (e.g., Luke et al., 2020). A key first step is identifying how cultivation affects local ecological and sociocultural dynamics. Although this has been done in many tropical contexts, large research gaps remain. From a spatial perspective, this is especially true in the African tropics. For example, a recent meta-analysis on the impacts of tropical agriculture on biodiversity found roughly 1.5 and 2.6 times more studies in the American and Asian tropics, than in the African tropics, respectively (Oakley and Bicknell, 2022). Traditional on-the-ground data collection (e.g., field surveys) is key to overcoming this knowledge gap and identifying the impacts of agriculture in poorly studied tropical regions. Yet, such data are often rare, owing to the challenge of collecting high-quality field data in remote or isolated areas and limited resources and availability of long-term funding in these regions.

Oil palm (*Elaeis guineensis*) is a cash crop that is grown widely across the tropics to produce palm oil: the most traded vegetable oil worldwide (USDA, 2023). Oil palm is economically important in producing regions (e.g., in 2019 alone, Indonesia's palm oil exports were valued at >16 billion USD (Statistik Perkebunan Unggulan Nasional 2019-2021, 2021), and it underpins the livelihoods of farmers in >45 official development assistance (ODA) countries (DAC List of ODA Recipients, 2023; FAOSTAT, 2023). Further, owing to its high productivity (oil palm yields 2.5–6 times more oil per unit area than soybean and oilseed rape, the next most grown vegetable oil crops), cultivation is essential to achieving global food security goals (Meijaard et al., 2020). However, oil palm plantations have also replaced >19.5 Mha of native tropical habitat (mostly lowland rainforest but also peatlands (Warren-Thomas

et al., 2022) and savanna (Fleiss et al., 2022)), driving declines in biodiversity (Barnes et al., 2014) and rates of ecosystem functioning (Dislich et al., 2017), and increasing greenhouse gas emissions (Drewer et al., 2021; Mori, 2023). For instance, a study in Indonesia (Barnes et al., 2014) showed that conversion of rainforest to oil palm caused plot-level species diversity, density, and biomass of invertebrates to decline by >45 %, and led to a 50 % reduction in energy fluxes (an indicator of multitrophic ecosystem functioning).

Most oil palm production occurs in Southeast Asia (Corley and Tinker, 2016, p. 12). Approximately 95 % of closed-canopy oil palm is in this region (Descals et al., 2021), with Indonesia and Malaysia alone producing about 80 % of the global palm oil supply (USDA, 2023). In Southeast Asia, oil palm is usually grown in three contexts: (1) by large-scale corporations in an industrial plantation-style setting (i.e., as a monoculture and with high chemical input, 'industrial oil palm'), (2) by individual farmers on variously-sized plots of land usually <50 ha in size ('smallholder oil palm'), or (3) by networks of smallholder farmers who receive technical assistance from large-scale corporations ('plasma oil palm' or 'nucleus oil palm') (Reiss-Woolever et al., 2021). Owing to the high levels of cultivation in Southeast Asia, most of our understanding of oil palm as a crop—and how its cultivation affects ecological and sociocultural dynamics—comes from this region. For instance, a recent systematic map on oil palm globally that quantified the extent of social, ecological, and interdisciplinary research found that nearly 75 % of studies occurred in Southeast Asia, out of a total of 443 (Reiss-Woolever et al., 2021). Of the remainder, 15 % were in Latin America, 8 % in Africa, and 1 % in Oceania. An associated systematic mapping exercise that focussed on within-plantation management practices found that 80 % of studies occurred in Southeast Asia (10 % in Latin America and 4 % in Africa) (Popkin et al., 2022).

However, oil palm cultivation is increasing rapidly outside of Southeast Asia, owing to rising employment costs, reduced land availability, and tighter environmental regulations in the region (Davis et al., 2020; Descals et al., 2021). The extent to which Southeast Asia-based findings are applicable to other regions where oil palm is grown is largely unknown. Africa is becoming a hub of palm oil production (Davis et al., 2020; Descals et al., 2021). Oil palm has been grown commercially in Africa since at least the eighteenth century, and using industrial plantation-style methods since about 1909 (Corley and Tinker, 2016, p. 5). Angola, Benin, Congo, Côte d'Ivoire, and Nigeria were the major African palm oil suppliers throughout most of the twentieth century (although Cameroon increased production from about 1985 onwards) (Corley and Tinker, 2016, p. 5). By 2012, the top-producing countries were Nigeria (940 kt of oil producer per year (kt yr^{-1})), Ghana (420 kt yr^{-1}), Côte d'Ivoire (420 kt yr^{-1}), and Cameroon (245 kt yr^{-1}) (Corley and Tinker, 2016, p. 12). Increases in African oil palm cultivation have been driven both by large-scale corporations and smallholder farmers. For instance, recent expansion in Southeast Liberia has been driven almost entirely by large-scale corporations (Davis et al., 2020), but expansion in Southwest Cameroon has been driven largely by smallholders (Ordway et al., 2017).

There are at least five key reasons why oil palm cultivation may have different impacts in Africa compared to other regions, precluding the application of Southeast Asia-based findings in African contexts, and making the case for why increased oil palm-focussed research in Africa is required urgently. First, there are extensive climatic and geophysical differences across the tropics. For instance, in comparison to Southeast Asia, many producing regions in Africa experience a drier climate and lower levels of solar radiation, both factors that influence oil palm growth and production and therefore the relative environmental impacts of palm oil production (Lamade et al., 1996; Rhebergen et al., 2016). Second, oil palm is native to Africa, having evolved in West Africa, and is found commonly today in lowland rainforest areas across West and Central Africa (Maizura et al., 2006). It has therefore co-evolved with other African species, possibly increasing the number of diseases and pests present, but potentially also resulting in heightened resilience against diseases and pests and higher numbers of beneficial interactions that enhance the delivery of key ecosystem services, such as pollination, that boost production. Tailored management—different from regions where oil palm has been introduced—is needed to account for these unique ecological dynamics, which could also result in more muted or stronger environmental impacts of cultivation. Third, because oil palm is native to Africa, it is cultivated using traditional approaches in addition to the smallholder, plasma, and industrial approaches that are practised in Southeast Asia and Latin America. Traditional approaches often involve harvesting from naturally-occurring groves of oil palms in lowland rainforest areas. Very little information is available about the impacts of traditional approaches to oil palm cultivation; how oil palm is used by local African people for food, medicinal, cultural, or other purposes; or how traditional cultivation practises vary across geographic space and cultural groups. Fourth, industrial-style expansion of oil palm in parts of Africa is being driven by Southeast Asia-owned companies (Davis et al., 2020), some of which implement management practises that were developed in Southeast Asia and could therefore have a different impact within Africa's unique ecological and sociocultural contexts. Fifth, there are substantial sociocultural differences between and within African, Southeast Asian, and Latin American cultural groups, owing to unique histories and current cultural and political dynamics in each region. As oil palm cultivation is inherently an ecological and sociocultural process, the impacts of production will be determined largely by the people affected by–and driving–its growth.

Additional ecological and sociocultural studies on the impacts of oil palm cultivation in an African context are needed urgently. However, the large-scale, field-based studies that are required to fill knowledge gaps around the impacts of oil palm cultivation in Africa – and therefore lay the groundwork for more sustainable palm oil production in this region – are lacking (we point to the SAFE Project (Ewers et al., 2011); EFForTS-Programme (Drescher et al., 2016); and BEFTA Programme (Luke et al., 2020) as flagship studies of this kind in Southeast Asia). In this paper, we introduce a new large-scale, field-based study – the Sustainable Oil Palm in West Africa (SOPWA) Project – that is investigating the relative socioecological impacts of oil palm cultivation in Southeast Liberia (West Africa). Importantly, our study–which is co-developed between academic, oil palm industry, government, and local community partners–considers both traditional and industrial approaches to oil palm cultivation, and compares conditions in these systems to rainforest, which is the dominant habitat in the study region and often a source of new oil palm farms, as a reference native habitat. Our paper is twofold in focus. First, we use systematic mapping methods to appraise the literature of oil palm-focussed studies in Africa, assessing the geographic and disciplinary focus of research to date and identifying clusters of research activity and knowledge gaps that preclude the development of more-sustainable oil palm cultivation in Africa. We then introduce the SOPWA Project, detailing our study region and ecological monitoring plots and—using canopy cover, ground vegetation cover, and soil temperature data as a case study—showcase the utility of our study design for assessing differences between rainforest and traditional and industrial oil palm systems.

2. Methods

2.1. Systematic mapping of research on oil palm in Africa

We used systematic mapping to quantify the extent and focus of existing research on oil palm in Africa and to identify knowledge gaps relating to traditional uses of oil palm and the ecological and sociocultural impacts of cultivation. Systematic mapping involves using a detailed procedure to locate, classify, and describe existing literature on a subject (James et al., 2016). In comparison to other recent oil palm-related systematic maps (e.g., Popkin et al., 2022; Reiss-Woolever et al., 2021), our methods specifically target—and therefore more comprehensively assess—oil palm-related research in an African context

(i.e., primary research based in Africa or occurring outside of Africa but, for instance, focussing on an oil palm germplasm that was collected in Africa or an oil palm-relevant species (e.g., *Fusarium oxysporum* f. sp. *elaeidis*) that was collected in Africa but examined elsewhere) and reported an ecological, socioeconomic, or interdisciplinary outcome. We concentrated on the disciplinary and geographic focus of studies over time, and did not appraise the quality of studies. We did not apply a date or language restriction (translating any non-English studies using Google Translate as needed and possible), although our methods are still biased linguistically since we only ran our search string in English. We adapted our methods from standard best practices published by the Collaboration for Environmental Evidence Systematic Review Guidelines (Sutherland et al., 2019), resulting in a five-stage workflow, the full details of which are in Supplementary Text 1 and Supplementary Fig. 1.

We found 757 unique publications which met our inclusion criteria. For these studies, we classed their scope(s) and outcome(s) into parent categories (Study scope parent categories: Interventions, Comparisons, Contexts; Outcome parent categories: Environmental Conditions, Production, Social Dynamics; Fig. 1) and concentric sub-categories (hereafter called "codes", Fig. 1; see Supplementary Tables 1 and 2 for parent category and code definitions for study scopes and outcomes, respectively). We established parent categories and codes from our existing knowledge of the global oil palm literature and consulting related systematic maps (e.g., Reiss-Woolever et al., 2021), adjusting our categories and codes as needed after reviewing the first 10 % of publications (Supplementary Text 1). All categories and codes were known to be potentially fruitful areas of work, to allow identification of research clusters and knowledge gaps. We allowed individual publications to fit into multiple parent categories and codes, as applicable. Therefore, the total number of individual (hereafter, 'occurrences') and co-occurring scopes and outcomes exceeds the number of publications. We also recorded date of publication, and the country (or countries) in which publications occurred (for which we also noted if the publication focussed on research across Africa (i.e., in no specific country) or if research occurred outside Africa but met our inclusion criteria (e.g., studies that used oil palm germplasms collected from Senegal, but with research taking place in Malaysia)). In line with our aim of identifying areas of research focus and knowledge gaps relating to traditional uses of oil palm and the impacts of cultivation, we also recorded whether studies focussed on traditional diets, uses, or practices associated with oil palm, if they were conservation oriented, and whether they were whole-ecosystem in focus (i.e., involving a range of taxonomic groups and ecosystem processes).

We analysed and visualised our findings using R (R Core Team, 2023) in RStudio (RStudio Team, 2023) using packages *tidyverse* (Wickham et al., 2019) and *pheatmap* (Kolde, 2022). First, we visualised changes in study frequency over time. Second, we assessed whether the location of studies (assessed at country-level) tracked to palm oil production. To do

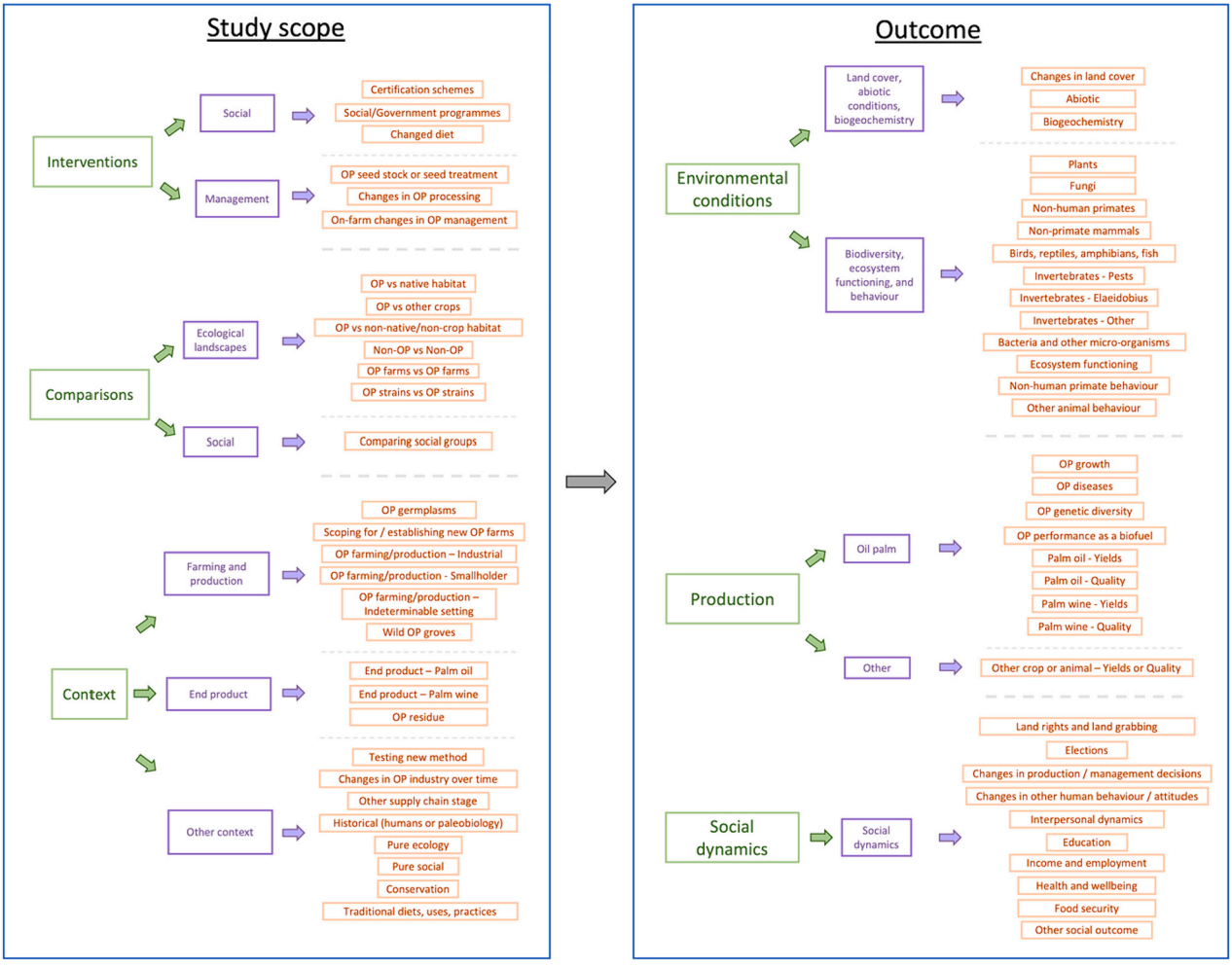

Fig. 1. Coding used to classify publications according to their study scope (Parent categories: interventions, comparisons, and context) and outcome (Parent categories: environmental conditions, production, and social dynamics). The categories in orange ('codes') were used for final classification and analysis. Definitions for parent categories and codes are provided in Supplementary Tables 1 and 2. Full details of our systematic mapping methodology are provided in Supplementary Text 1. OP = oil palm.

this, we extracted country-level data on palm oil production (tonnes of oil produced, '*Production*') from the database of the Food and Agriculture Organization (FAOSTAT, 2023), using 2019 values to prevent influence of the COVID-19 pandemic on our findings. We acknowledge that FAO crop production data can be biased, for instance, country-level statistics rarely include data from home gardens, which are common in sub-Saharan Africa (Galhena et al., 2013). Therefore, these data may be more indicative of production that influences national trade (FAOSTAT, 2023). Before plotting these data, we excluded publications that occurred across Africa generally (i.e., in no specific country; 36 studies) and publications that occurred outside of Africa (e.g., studies in Malaysia that worked with oil palm germplasms from Senegal; 63 studies). A total of 658 publications remained. We did not assess whether the location of studies tracked to palm wine production, as palm oil is the dominant oil palm product globally and statistics on palm wine are less available. Finally, we produced a heatmap to assess areas of research focus (i.e., co-occurrences between study scopes and outcomes) and to identify knowledge gaps relating to traditional uses and impacts of oil palm cultivation. We included data from all 757 publications in our heatmap.

2.2. *The Sustainable Oil Palm in West Africa (SOPWA) Project: A whole-ecosystem approach to understanding the relative impacts of traditional and industrial approaches to oil palm cultivation in Liberia*

2.2.1. *Study site*

Our new project – the Sustainable Oil Palm in West Africa (SOPWA) Project – occurs in Sinoe County, Liberia (West Africa) (Fig. 2), an area in which oil palm is native and where it has likely been harvested by local people for thousands of years (Corley and Tinker, 2016, p. 1; Kay et al., 2019). Sinoe County falls within the forest zone of West Africa (Upper Guinea in the phytogeographical literature, and included in the West African Forests ecoregion), running from Sierra Leone in the west to the Dahomey Gap (Ghana) in the east, from the coast up to 350 km inland (Marshall et al., 2021; White, 1979). The typical flora is lowland evergreen rainforest, with variations in species composition driven by gradients in rainfall, disturbance and local topology, with altitude and historical climatic stability important at broader geographical scales (Marshall et al., 2022). This area is recognised as a biodiversity hotspot (Myers et al., 2000; Olson et al., 2001), for instance, it is home to a high concentration of globally rare plant species (Bongers et al., 2004; Marshall et al., 2016, 2022). Liberia retains the highest density of rainforest in West Africa, although about one-fifth of its forested area has been lost to agricultural, logging, and mining activities (Davis et al., 2020). Most of this deforestation has occurred since 2003, when 15 years of domestic conflict ended and after which the Government of Liberia sold large areas of land to foreign investors as part of its economic re-development plan (Davis et al., 2020). Sinoe County has an estimated 891,806 ha of forest (about 88 % of its total area), and is the most forested county in Liberia (Forestry Development Authority, 2019). In Sinoe County, mean annual temperature is 25.4 °C, and mean annual rainfall is 3633 mm (calculated over 1970–2000; (WorldClim, 2023)). Sinoe County experiences two wet (April – June; September – October) and dry (July – August; November – March) seasons annually (Supplementary Fig. 2).

Traditionally, local people in Sinoe County have relied on shifting

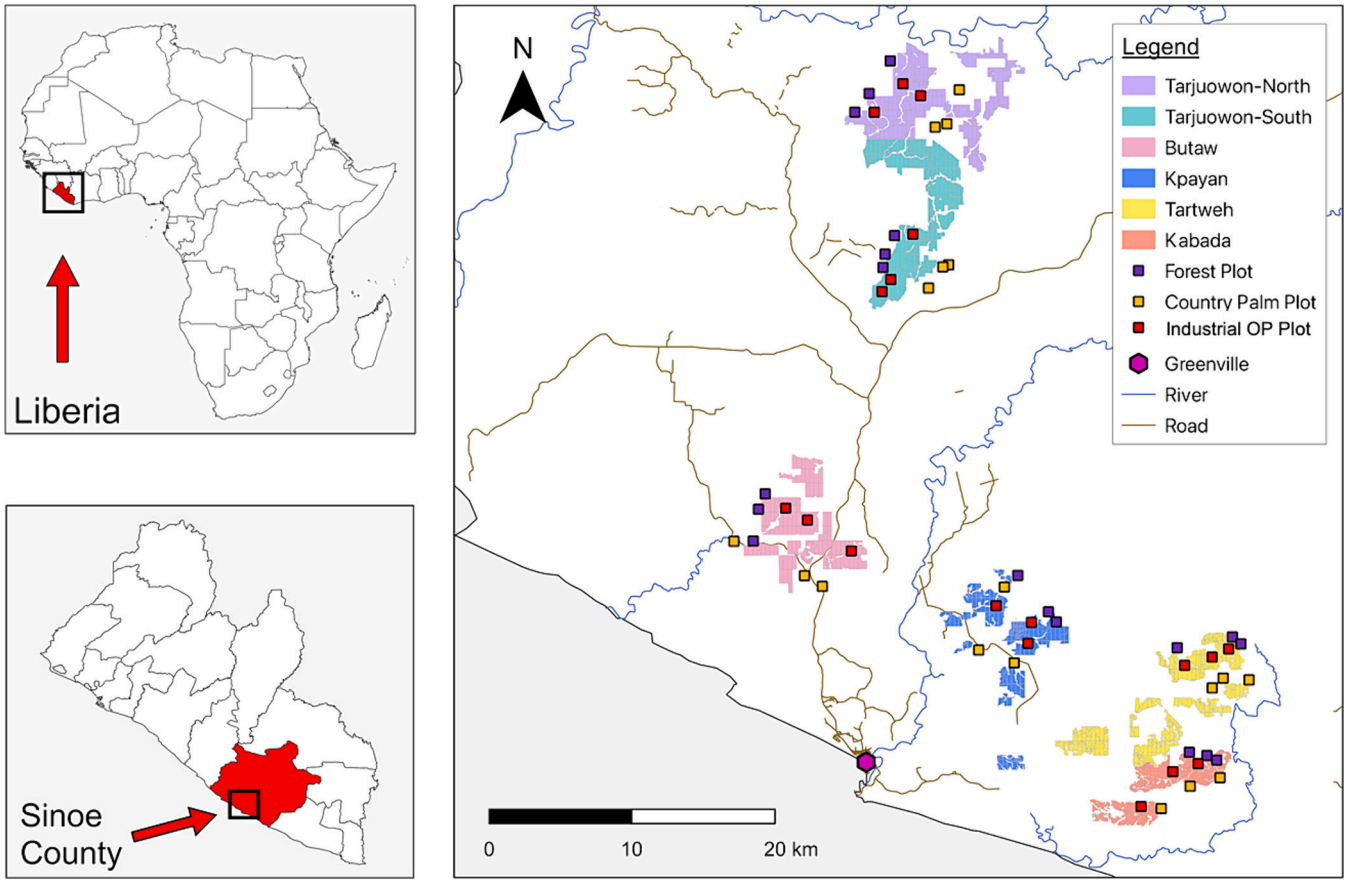

Fig. 2. Map of the SOPWA Project study area in Sinoe County, Liberia, which features study plots (50 × 50 m) in forest ($N = 18$; purple squares), country palm (N = 18; orange squares), and industrial oil palm ('Industrial OP' in legend, N = 18; red squares) systems. Plots are spatially clustered in and around each of six industrial oil palm farms: Tarjuowon-North (purple), Tarjuowon-South (turquoise), Butaw (pink), Kpayan (blue), Tartweh (yellow), and Kabada (peach). The city of Greenville (pink hexagon), the capital of Sinoe County, is shown as a reference. Blue and brown lines indicate major rivers and roads, respectively.

cultivation for their livelihoods. This involves burning small areas (often around 1 ha) of rainforest annually to improve soil fertility for cultivation of a variety of crops, including rice, cassava, yams, and banana (Sinoe County Development Agenda, 2012). Burning usually occurs at the end of the dry season (typically February or March), with crops planted soon after as the rainy season begins. When preparing lands for farming, local people often choose areas with wild-growing oil palms (called 'country palms' by local communities), which are fire-tolerant and therefore survive the burning process (Sowunmi, 1999). The density of palms within local farms varies, but care is taken to ensure that the density of palms is low enough to allow other crops, such as cassava, to receive sunlight, even if the country palms are fully grown. Country palms are a food staple in this region, with local people using the palms to produce products such as cooking oil and palm wine.

Oil palm is also cultivated in Sinoe County in industrial farms (although "plantation" is commonly used to describe industrial oil palm settings, we specifically use "farm" in line with the oil palm terminology used in Liberia), most of which were established by Golden Veroleum Liberia (GVL). GVL is the largest oil palm developer in Liberia and a member of the Golden Agri-Resources (GAR) group, a Singapore-based company that manages oil palm farms in thirteen countries. Other industrial oil palm farms in Liberia are found in Grand Cape Mount and Gbarpolu Counties (originally established by Sime Darby and now owned by Mano Palm Oil Industries) and Grand Gedeh County (originally established by the Liberian Ministry of Agriculture, and now managed by community cooperatives). In 2010, the Government of Liberia and GVL signed a Concession Agreement, which granted GVL a concession area of 220,000 ha of non-private land across the Counties of Sinoe, Grand Kru, Maryland, River Cess, and River Gee on which to conduct activities related to the production of oil palm products (Government of Liberia, 2010). When the Concession Agreement was signed, about 80 % of the GVL concession area was forested (i.e., having tree cover with >50 % canopy density; Global Forest Watch, 2014), with the remainder being other land types including existing smallholder agriculture and savanna (but with no savanna in Sinoe County). Owing to this, forest is the most appropriate baseline in Southeast Liberia, although the country palm approach to cultivation could also be viewed as a baseline in situations when existing agriculture is converted to industrial oil palm farms in the region. GVL is currently cultivating oil palm on ~ 19,000 ha of its concession area, and has set-aside almost 11,500 ha as High Conservation Value (HCV) areas. GVL established its first oil palm farms in Sinoe County in 2012, and currently has six oil palm farms in the County: Tarjuowon-North, Tarjuowon-South, Butaw, Kpayan, Tartweh, and Kabada.

2.2.2. Study aim, design, and surveys conducted to date

The SOPWA Project is investigating the relative socioecological impacts of traditional and industrial oil palm cultivation. The core of our project is 54 monitoring plots, established in February 2022 and each measuring 50 × 50 m in area (Supplementary Table 3), which span a 56 km distance in Sinoe County, Liberia (Fig. 2) and in three distinct systems:

1) *Forest* – These plots are in areas of old-growth Western Guinean lowland rainforest with no record of substantial disturbance. These areas are owned by GVL (called the 'GVL buffer', as they surround GVL's oil palm farms), and are used by local people for hunting, harvesting of non-timber forest products (NTFPs), and spiritual and cultural purposes. We placed plots in areas where the forest was continuous (i.e., we did not place plots in isolated forest fragments surrounded by oil palm or other habitats). As about 88 % of Sinoe County is forested, and forest is frequently a source of new farms, it is an ideal reference habitat (Forestry Development Authority, 2019).

2) *Country palm* – These plots are in fallowed traditional farms, established using slash-and-burn practises as described above. Farms had been abandoned for at least two years (mean: 7.6 years; range: 2–30 years; Supplementary Table 4), but local people still maintain and visit the area to harvest country palms (i.e., wild-growing palms, which either survived the burning process or established naturally after farms were fallowed). Various crops had been farmed previously in country palm plots, with the most commonly farmed crops being rice and cassava (each farmed in 14 plots), and cucumber, pepper, and bitterball (each farmed in 12 plots) (Supplementary Table 4). Today, these are areas of dense regrowth (called "low bush" by local communities). We found plots by asking local community members where they harvest their oil palm fruits. Chemical fertilisers, herbicides, or pesticides have never been applied within these plots. Although rainforest is the most representative reference habitat in Sinoe County, country palm could also be viewed as a baseline in situations when existing agriculture is converted to industrial oil palm farms.

3) *Industrial oil palm* – These plots are in GVL oil palm farms. Farms are organised into 300 × 1000 m blocks, separated by dirt roads, with palms planted approximately 8 m apart in a staggered design. All farms are oil palm monocultures, intersected by riparian reserves (composed of native rainforest, and ranging from about 25–125 m in width from either riverside) and conserved forest fragments (typically where villages were previously, and therefore fragments are differently sized and valuable culturally to local communities). The farms were not managed identically, but were all managed according to business-as-usual practices that were developed in Sumatra, Indonesia, including regular application of fertilisers, herbicides, and pesticides (when outbreaks of insect pests occur). Palms are harvested manually (using a chisel for younger palms, and a harvesting sickle on a telescopic pole for taller, more mature palms) at 10–15 day intervals. In comparison to country palms, industrial oil palms consist of high-yielding varieties purchased from the suppliers PalmElit, Socfindo, and Dami Mas. When our project started in February 2022, palms in our plots were aged between four and ten years (i.e., all were fruiting), with 50 % of palms in plots being aged six or seven years (Supplementary Table 5).

Our plots are arranged in six clusters, located in and around each of the six GVL oil palm farms in Sinoe County (Fig. 2). There are nine plots in each cluster (three plots per system per cluster), and we have ensured that same-system plots within a cluster are at least 400 m apart to minimise spatial correlation (mean: 1853 m apart; range: 442–5530 m apart). The mean elevation of plots is 116 m above sea level (range: 14–211 m above sea level) (Supplementary Table 3). We aimed to place forest and industrial oil palm plots at least 200 m from GVL farms and surrounding forest, respectively, as studies from Southeast Asia show that this distance is sufficient to prevent edge effects on tropical rainforest and agricultural communities (Chapman et al., 2019; Lucey and Hill, 2012). However, two forest plots are within this distance (149 and 159 m from the surrounding oil palm), and the mean distance of forest plots from GVL farms is 256 m (range: 149–433 m). The mean distance of industrial oil palm plots from surrounding forest is 616 m (range: 306–1093 m). We aimed to place country palm plots at least 200 m from GVL farms to mitigate the influence of farms on ecological processes within the country palm plots. However, as the location of country palm plots was determined by where local communities had previously farmed and still harvested country palms, this was not always possible, and the mean distance of country palm plots from GVL farms is 602 m (range: 72–1212 m).

We have so far surveyed our plots in February – March 2022 and January – February 2023, assessing environmental conditions, the biodiversity of a range of taxonomic groups, and levels of ecosystem functioning, to determine the relative ecological differences between rainforest, country palm, and industrial oil palm systems. For environmental conditions, we recorded canopy cover, vegetation structural complexity, and understory vegetation cover. For biodiversity, we surveyed trees, understory plants, birds, insectivorous bats, ground-dwelling mammals, spiders, and insects. For ecosystem functions, we measured seed removal, ant scavenging activity, forest regeneration, and soil invertebrate feeding activity. We have also conducted socio-cultural surveys, including assessing the social, cultural, medicinal,

spiritual, and economic benefit of plant species in our plots to local communities. Before any fieldwork, we met with local chiefs and communities and obtained approval for our work. While sampling, we paid for site access and worked with and compensated local people for their time. Local representatives were nominated from the local community, and to date have always been men. We moved five plots (one forest plot and four country palm plots) <200 m between our 2022 and 2023 surveys, owing to slash-and-burn activity that had disturbed the previous year's plot location (Supplementary Table 3).

2.2.3. Demonstrating the utility of the SOPWA Project study design: Assessing differences in canopy cover, ground vegetation cover, and soil temperature across land use systems

2.2.3.1. Data collection. In this paper, we use canopy cover, ground vegetation cover, and soil temperature data from our plots, as a case study to demonstrate the utility of the SOPWA Project study design for investigating the ecological impacts of traditional and industrial oil palm cultivation, and to provide contextual data for forthcoming studies. We measured canopy cover by placing an iPhone 8 on an outstretched hand at waist-height, such that the elbow formed a 90° angle, and taking four upwards-facing photos (in each of the cardinal directions) at the corners and centre of each plot. Using Adobe Photoshop (Version 23.3), we separated pixels containing sky or vegetation using the built-in edge detection algorithm. We corrected for any pixels that were mistakenly assigned by making further additive selections as needed, after adjusting the tolerance parameters for hue, saturation, and luminosity in each photo. Ground vegetation cover was measured by estimating the percent area of ground that was covered by vegetation in a 1 m^2 area at three locations in each plot (each 5 m from the plot centre at bearings 0°, 135°, and 225°, and 10 m from each other). Soil temperature was measured by burying an iButton® datalogger (Measurement Systems Ltd., Berkshire, UK) at 5 cm depth at the centre of each plot. Dataloggers were programmed to record temperature every hour over a 48-h period. Two dataloggers failed in the field (one each in country palm and industrial oil palm) and therefore we only collected data from 52 plots. Canopy cover data were collected in February – March 2022, and ground vegetation cover and soil temperature data were collected in January – February 2023. This time period corresponds to the Liberian dry season (Supplementary Fig. 2).

2.2.3.2. Statistical analysis. We analysed data using R (R Core Team, 2023) in RStudio (RStudio Team, 2023) using packages *tidyverse* (Wickham et al., 2019), *glmmTMB* (Magnusson et al., 2019), *cowplot* (Wilke, 2023), *DHARMa* (Hartig and Lohse, 2022), *gamm4* (Wood and Scheipl, 2020), and *multcomp* (Hothorn et al., 2023).

We analysed differences in canopy cover and ground vegetation cover across systems using generalised linear mixed models (GLMMs) that were fitted to beta distributions. Prior to analysis, we averaged canopy cover and ground vegetation cover values in each plot and used the per-plot average as our unit of analysis. To meet the requirements of *glmmTMB,* we transformed our ground vegetation cover data to be between 0 and 1 prior to analysis using the equation:

$$(Y^{*}\,(N-1)+0.5\,)/N$$

Wherein Y = the untransformed per-plot ground vegetation cover values, and N = the number of plots we sampled (i.e., 54). We did not transform canopy cover data, as per-plot values were already between 0 and 1. We fitted *System* (levels: Forest, Country palm, Industrial oil palm) as a fixed effect and *Farm* (levels: Tarjuowon-North, Tarjuowon-South, Butaw, Kpayan, Tartweh, Kabada) as a random intercept effect, to account for the spatial clustering of our plots in our modelling. Our models therefore took the form: $Canopy\_cover \sim System + (1 \mid Farm)$ and $Vegetation\_cover \sim System + (1 \mid Farm)$. We validated our models by plotting Pearson residuals against fitted values and covariates and ensuring no patterns were present (Zuur and Ieno, 2016). We simulated 10,000 datasets from each model, calculated dispersion statistics for each simulated dataset, and verified that the simulated dispersion statistics tracked to that of the underlying model. We determined the significance of *System* to the response by comparing fitted models to null models using likelihood ratio tests (LRTs). When *System* was significant ($P < 0.05$), we conducted pairwise post-hoc tests to determine differences between systems, using Tukey all-pair comparison tests (using *glht ()* in *multcomp* (Hothorn et al., 2023).

We analysed differences in soil temperature across systems using a generalised additive mixed model (GAMM). We fitted our model to a Gaussian distribution (identity link) and fitted a smoothing function (using a 20-knot cyclic penalised cubic regression spline, multiplied by *System*) to the time of day at which recordings occurred, to account for *System*-dependent non-linearity of temperature changes across the day. As we measured soil temperature in each plot over two days, we nested *Plot* within *Farm* as a random effect. Our model therefore took the form: $Temperature \sim System + s(Time,\ by = System) + (1 \mid Farm/Plot)$. Our model validation procedure included plotting and visually inspecting quantile-quantile plots to ensure a linear pattern was present, plotting Pearson residuals against fitted values and covariates and ensuring no patterns were present, and ensuring that Pearson residuals were normally distributed. We used analysis of variance (ANOVA) to determine the significance of covariate *System* (Zuur et al., 2014). To assess whether multiplying the smoother by *System* significantly improved the model, we fitted a null model ($Temperature \sim System + s(Time) + (1 \mid Farm/Plot)$) and calculated and compared the Akaike Information Criteria (AIC) for our null and fitted models. We interpreted that the model with a higher AIC was poorer, if the difference in AICs was greater than two (Zuur et al., 2014). To determine differences in soil temperature between systems, we applied a Bonferroni correction to our posthoc analysis (using *glht()* in *multcomp* (Hothorn et al., 2023)) to account for multiple comparisons.

3. Results

3.1. Systematic mapping of research on oil palm in Africa

3.1.1. Temporal and spatial distribution of publications

We found 757 unique publications that met our inclusion criteria, published between 1942 and 2023, with the number of studies increasing over time (Fig. 3A) and generally tracking to global patterns in oil palm-related research (Supplementary Fig. 3). After eliminating studies that did not occur in Africa but met our inclusion criteria, publications occurred in 36 African countries, with the most-represented countries being Nigeria ($N = 224$), Ghana ($N = 112$), Cameroon ($N = 106$), Côte d'Ivoire ($N = 76$), and Benin ($N = 52$) (Fig. 3B). Generally, the amount of oil palm-focussed research in each country tracked to its levels of palm oil production, although there was some variability (Fig. 3B). For instance, in Cameroon there have been 1.4 and 4.5 times more publications than in Côte d'Ivoire and Democratic Republic of the Congo, although levels of palm oil production between these countries are similar (in 2019, Cameroon, Côte d'Ivoire, and Democratic Republic of the Congo produced 2.62, 2.46, and 2.12 megatonnes of palm oil, respectively). Although FAO data indicate that Uganda does not produce palm oil, five publications reported oil palm farms in the country, and we are aware of Uganda-based plantations owned by international palm oil corporation Wilmar (Wilmar International, 2024). São Tomé and Príncipe was the only country with FAO-reported palm oil production but no oil palm-focussed research (Fig. 3B).

3.1.2. Extent and focus of oil palm research, and identifying knowledge gaps

Study scopes included interventions (152 occurrences), comparisons (564 occurrences), and contexts (1186 occurrences). The most studied intervention was on-farm changes in oil palm management (63

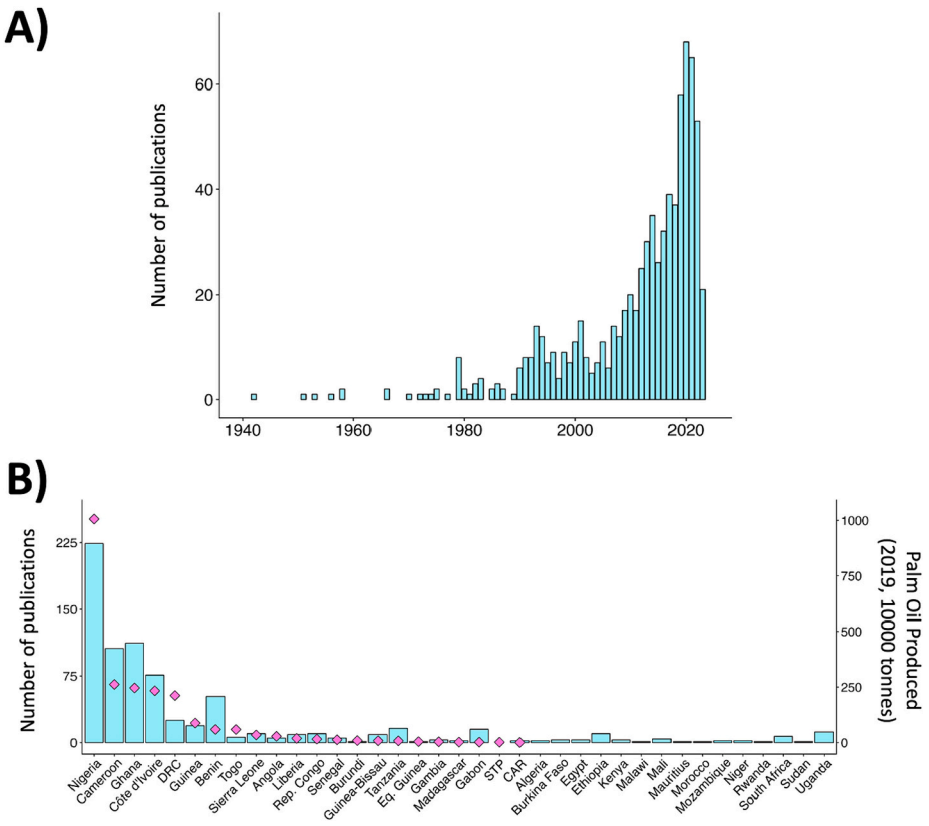

Fig. 3. (A) Number of publications meeting our inclusion criteria over time and (B) the countries in which publications occurred. In (A), all 757 publications meeting our inclusion criteria are represented, and bar charts indicate the number of studies published each year (range: 1942–2023). In (B), we removed publications that occurred across Africa generally or occurred outside Africa but met our inclusion criteria (e.g., studies in Malaysia that used oil palm germplasms from Senegal). 658 publications are represented. Bar charts indicate the number of publications occurring in each country, and diamonds indicate the amount of palm oil produced per country (expressed per 10,000 t and using FAO data from 2019 (FAOSTAT, 2023). Countries are ordered by palm oil production (highest to lowest). Countries without bar charts or diamonds indicate those where no publications occurred or that do not produce palm oil (according to the FAO), respectively. CAR = Central Africa Republic; DRC = Democratic Republic of the Congo; Eq. Guinea = Equatorial Guinea; Rep. Congo = Republic of the Congo; STP = São Tomé and Príncipe.

occurrences). The most studied comparison was between oil palm and other crops ('OP vs other crops', 178 occurrences), followed by comparisons of oil palm farms ('OP farms vs OP farms', 124 occurrences) and oil palm and native habitat ('OP vs native habitat', 75 occurrences). Oil palm production was a frequently studied context, and smallholder oil palm (86 occurrences) was slightly more studied than industrial oil palm (76 occurrences), although production settings were often not indicated and therefore indeterminable (149 occurrences). Although oil palm is native to Africa, studies on wild oil palm groves were uncommon (28 occurrences). Palm oil as an end product (144 occurrences) was more studied than palm wine (34 occurrences). Studies were often purely ecological in focus (111 occurrences) or purely social in focus (87 occurrences) (Fig. 4A). 77 publications were conservation-oriented, and 79 publications focussed on traditional diets, uses, and practices associated with oil palm.

Outcomes included environmental conditions (532 occurrences), production (392 occurrences), and social dynamics (500 occurrences). The most studied environmental condition was abiotic conditions (96 occurrences); the most studied production outcome was palm oil yields (80 occurrences); and the most studied social dynamic was health and wellbeing (152 occurrences). Although Africa is a growing hotspot of oil palm development, studies reporting on land rights and land grabbing were uncommon (20 occurrences) (Fig. 4B).

The commonest area of research focus (i.e., co-occurrence of study scope and outcome) was between palm oil as an end product and human health and wellbeing (91 co-occurrences), followed by palm oil as an end product and palm oil quality (50 co-occurrences) and purely social studies and human health and wellbeing (48 co-occurrences) (Fig. 5). In smallholder oil palm settings, most research focussed on social dynamics (165 co-occurrences), followed by production (41 co-occurrences) and environmental conditions (34 co-occurrences). However, we found the opposite pattern in industrial settings, with the most research focussed on environmental conditions (70 co-occurrences), followed by production (47 co-occurrences) and social dynamics (44 co-occurrences). In wild oil palm groves, most research focussed on environmental conditions (39 co-occurrences), namely chimpanzee behaviour (13 co-occurrences) (Fig. 5).

Our systematic map revealed several key knowledge gaps relating to traditional uses of oil palm and the ecological and sociocultural impacts of cultivation. For instance, research on traditional diets, uses, and practices and all outcomes, aside from human health and wellbeing (43 co-occurrences), was rare. Research on certification schemes and all outcomes was also rare, with no co-occurrences between certification schemes and environmental conditions, only one co-occurrence with production, and 7 co-occurrences with social dynamics (Fig. 5). No research programme (i.e., a single publication or group of publications by similar authors and occurring in the same geographic space) has evaluated the whole-ecosystem (i.e., involving a range of taxonomic groups and ecosystem processes) impacts of oil palm cultivation in any African production setting (Supplementary Table 6).

3.2. The Sustainable Oil Palm in West Africa (SOPWA) Project: A whole-ecosystem approach to understanding the relative impacts of traditional and industrial approaches to oil palm cultivation in Liberia

Our case study—in which we demonstrate the utility of the SOPWA

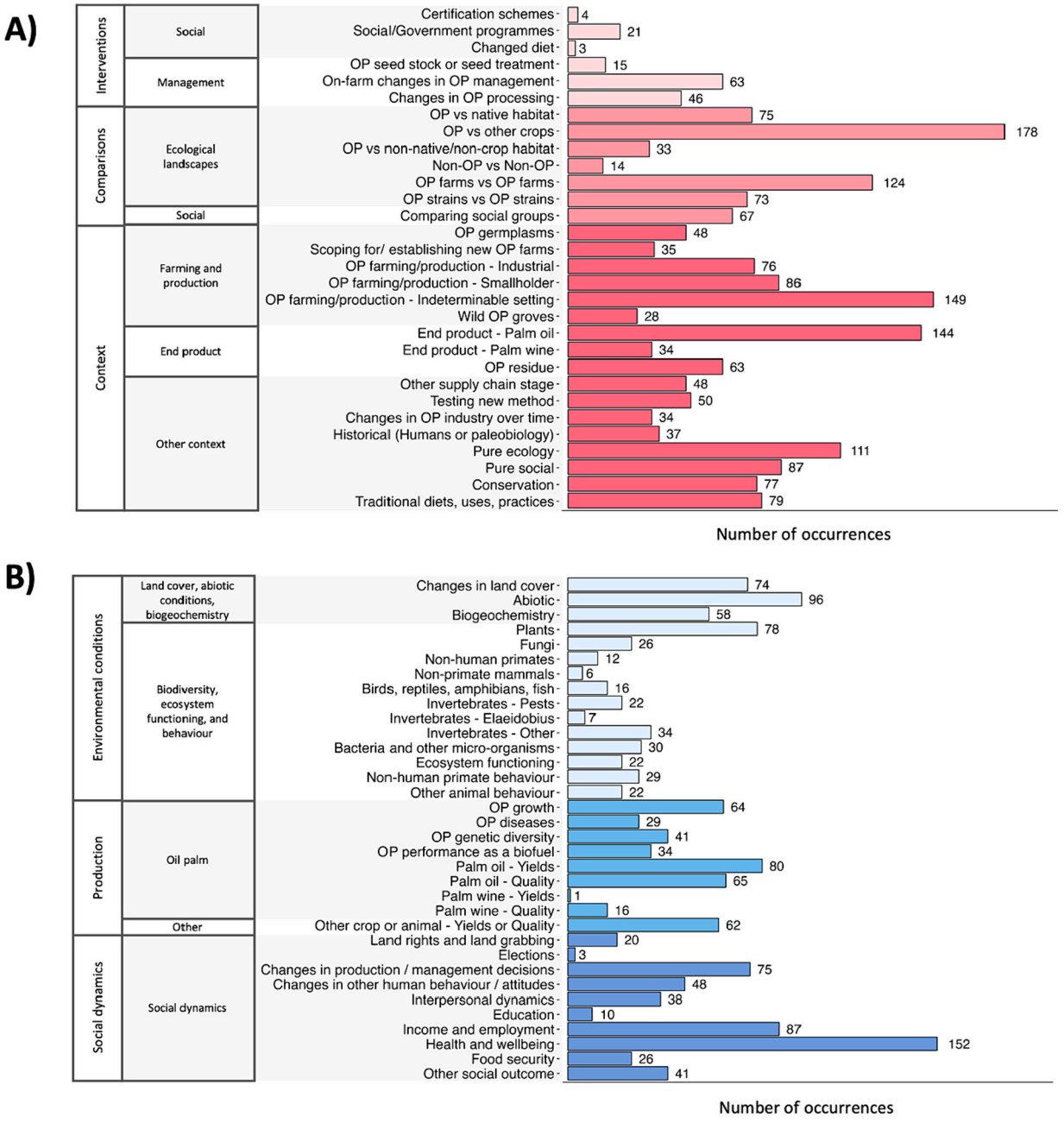

Fig. 4. (A) Study scopes and (B) outcomes – and their respective occurrences – across studies. Individual publications can appear in more than one code in (A) and (B), as publications often focussed on multiple interventions, comparisons, contexts, and outcomes. Alternations in background colour between grey and white are to aid visualisation. Codes are organised according to the groups outlined in Fig. 1 and are defined in Supplementary Tables 1 and 2.

Project study design for investigating the ecological impacts of traditional and industrial oil palm cultivation—indicated differences in canopy cover (LRT = 24.693, $P_{System} < 0.001$), ground vegetation cover (LRT = 61.743, $P_{System} < 0.001$), and soil temperature (F = 22.23, $P_{System} < 0.001$) across rainforest, country palm, and industrial oil palm systems (Fig. 6A-C). Canopy cover in rainforest ($\bar{X}$ (mean) ± SE (standard error) = 91.3 % ± 0.9 %) was 1.3 and 1.4 times higher than in country palm (68.2 % ± 3.8 %, $P_{Comparison} < 0.001$) and industrial oil palm (65.2 % ± 5.3 %, $P_{Comparison} < 0.001$), respectively (Fig. 6A). Ground vegetation cover in rainforest (97.8 % ± 0.2 %) was 1.3 and 1.7 times higher than in country palm (72.8 % ± 3.8 %, $P_{Comparison} < 0.001$) and industrial oil palm (56.4 % ± 4.3 %, $P_{Comparison} < 0.001$), respectively. Ground vegetation cover in country palm was 1.3 times higher than in industrial oil palm ($P_{Comparison} = 0.002$) (Fig. 6B). Soil temperature varied significantly across the day in all systems ($P_{Smoother} < 0.001$ for all; $AIC_{Fitted} = 3909$, $AIC_{Null} = 4854$), but the degree of variability was not the same. Cross-day variability in industrial oil palm (24–- 36.5 °C) was higher than that in country palm (23.5–29.0 °C, $P_{Comparison} < 0.001$) and rainforest (24.0–26.0 °C, $P_{Comparison} < 0.001$). We did not detect differences in cross-day variability between rainforest and country palm, but temperatures between these systems varied substantially in the afternoon. Differences between all three systems peaked at 16.00, when average soil temperature was 28.3 °C in industrial oil palm, 26.5 °C in country palm, and 25.4 °C in rainforest (Fig. 6C).

4. Discussion

In this paper, we introduce the Sustainable Oil Palm in West Africa

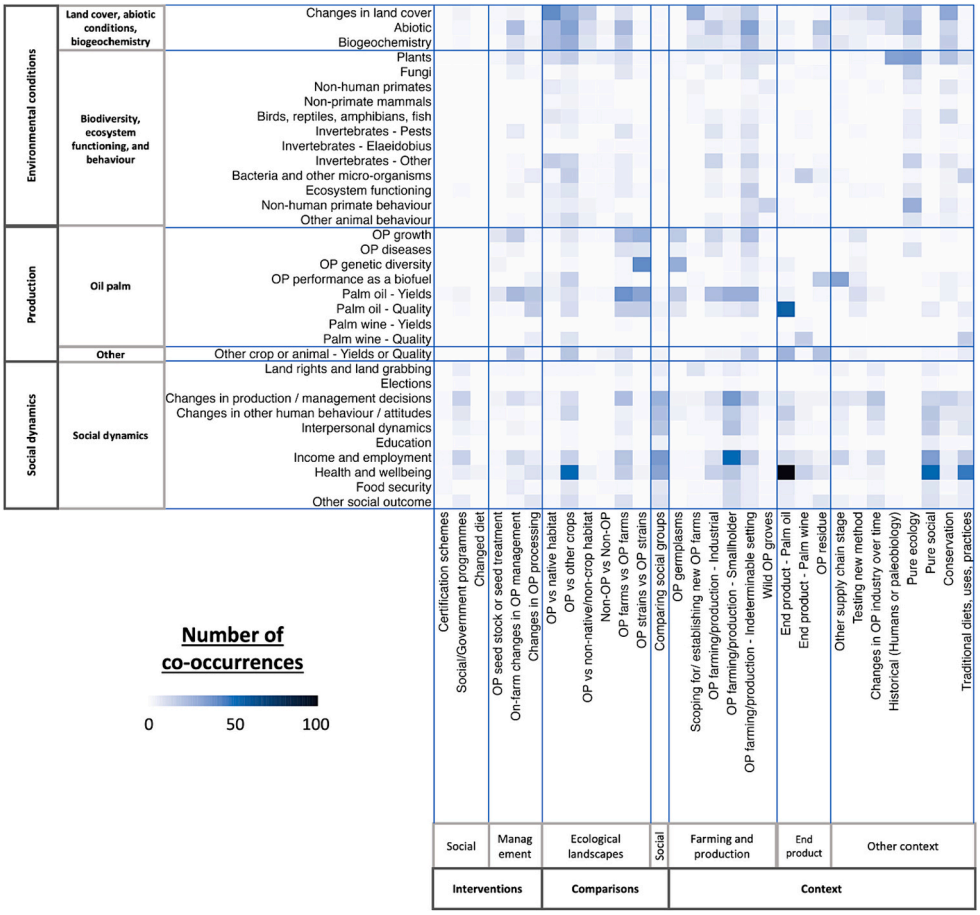

Fig. 5. The co-occurrence of study scopes (parent categories: interventions, comparisons, context) and outcomes (parent categories: environmental conditions, production, social dynamics) in the 757 publications. Darker cells have higher co-occurrence frequencies. An individual publication can fall into multiple cells. Codes are organised according to Fig. 1 and are defined in Supplementary Tables 1 and 2.

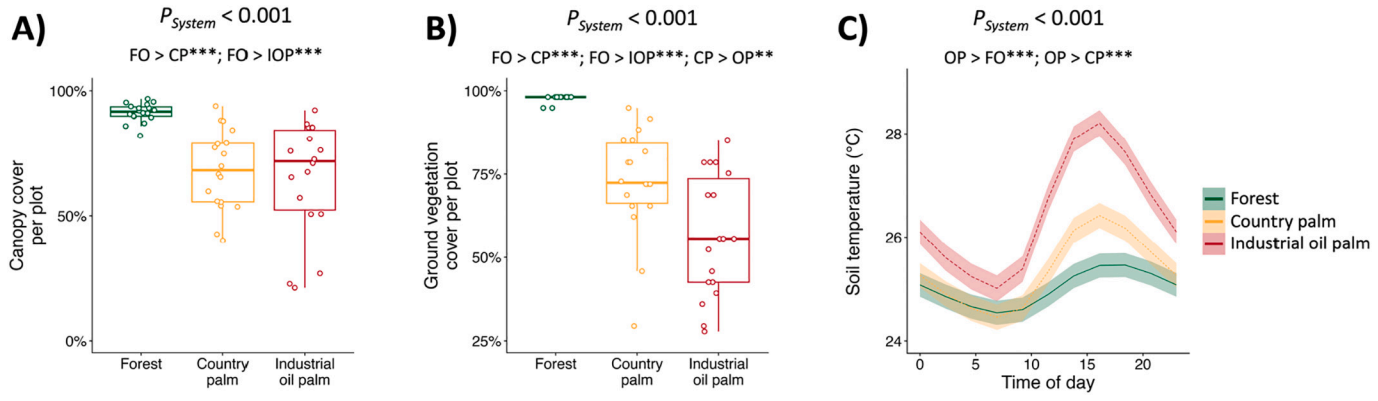

Fig. 6. Differences in (A) canopy cover, (B) ground vegetation cover, and (C) soil temperature across forest, country palm, and industrial oil palm systems. For (A) and (B), boxplots display median and interquartile ranges, and per-plot values are shown as circles. For (C), lines represent outputs from the GAMM (with 95 % confidence intervals). We did not plot raw temperature data to aid visualisation, as data were collected at hourly intervals ($N = 2496$).

(SOPWA) Project. To contextualise the Project, we provided a systematic map that quantifies the extent of research on oil palm in Africa to date. Our map demonstrated that most research has focussed on human health and livelihoods and revealed several key knowledge gaps, including that no study has yet assessed the whole-ecosystem impacts of palm oil production in Africa. The SOPWA Project directly addresses this and is additionally assessing sociocultural impacts of production. We demonstrated the utility of the SOPWA Project's study design to show that—in comparison to rainforests— traditional and industrial oil palm systems support lower levels of canopy cover and ground vegetation cover and have hotter and more variable soil temperatures.

4.1. Systematic mapping of oil palm research in Africa

In comparison to Southeast Asia and Latin America, oil palm-focussed research in Africa – oil palm's native range – is uncommon (Reiss-Woolever et al., 2021). Ours is the most comprehensive systematic map of oil palm-focussed research in Africa to date. We found that

research activity has increased in recent years, possibly owing to general increases in research activity worldwide but also increases in palm oil production across Africa (Davis et al., 2020), to meet heightened demands for palm oil for use in food, cosmetics, and biofuels. We found publications occurring in all palm oil-producing African countries, according to the FAO, except for São Tomé and Príncipe (we note that there is at least one study (De Lima et al., 2013) from São Tomé and Príncipe that sampled oil palm, but oil palm was only mentioned once in the manuscript and was not a focus of the study and therefore was not detected by our search string). As São Tomé and Príncipe is an island nation and therefore likely supports a high number of endemic or migratory species, future studies focussing on the ecological impacts of oil palm cultivation within-country may be particularly valuable. Publications in countries where oil palm is not reported to be grown (Burkina Faso, Malawi, Mali, Mauritius, Morocco, Mozambique, Niger, South Africa, Sudan, and Uganda), according to the FAO, mostly focussed on the consumption of imported palm oil. In a few cases (e.g., Amugoli et al., 2020; Baguma et al., 2019; Egonyu et al., 2021, which occur in Uganda), data collection occurred within oil palm plantations, and this is likely an artefact of FAO data being biased towards palm oil that is exported (FAOSTAT, 2023).

Our systematic map indicated that the most common study scope was comparing oil palm and other crops. In comparison, another systematic map that assessed 443 oil palm-related studies occurring worldwide found that comparisons between oil palm and native habitat were most common (Reiss-Woolever et al., 2021). This difference in findings could reflect a changing focus of oil palm research, as our map had a higher proportion of studies from more recent years. While comparing oil palm to other crops and native habitat is valuable for understanding its relative ecological and sociocultural impacts, increased attention on management within farms is also needed to develop tractable strategies that enhance the sustainable production of palm oil and palm wine, and more directly inform the development of Africa-specific sustainability certification criteria and on-farm interventions that individual farmers can implement. The most studied outcome was human health and wellbeing, broadly tracking to research patterns found globally by Reiss-Woolever et al. (2021), and reflecting the importance of crude palm oil (also called red palm oil) in traditional African dishes and its importance as a source of Vitamin A in many African countries (Bechoff et al., 2018).

Our map indicated research in several study scopes and outcomes that are unique to an African context. Africa-specific study scopes included studying wild-growing groves of oil palm, palm wine as an end product, historical studies focussed on human history (including ancient human history) or paleobiology, and traditional diets, uses, and practices associated with oil palm. Africa-specific outcomes included palm wine yields and palm wine quality. As harvesting of wild-growing oil palms, and production and consumption of palm wine, does not take place in other tropical regions, these are areas where novel research can and should be conducted. Understanding Africa-specific contexts and outcomes of oil palm growth and production is key to unlocking more-sustainable production of oil palm across Africa.

Although environmental outcomes were somewhat well-studied, we found that publications focussed on only one or a few taxonomic groups or ecosystem processes, and that there were no publications or research programmes that had evaluated the whole-ecosystem impacts of oil palm cultivation in Africa. Further, studies focussed on conservation aspects were rare (about 10 % of all studies). This is not the case in other producing regions such as Southeast Asia (Reiss-Woolever et al., 2021). Research is needed urgently in Africa to understand how oil palm cultivation affects native ecosystems. This is important from both conservation and management perspectives as – once they are established – oil palm farms could support relatively high numbers of species compared to other agricultural systems (Foster et al., 2011), many of which provide ecosystem services that boost palm oil yields (Dislich et al., 2017). Further work is therefore needed to identify and boost the biodiversity of native African species that enhance productivity and profitability in existing oil palm systems.

No studies investigated the impacts of sustainability certification programmes on environmental conditions, and only one study (Brako et al., 2021) and three studies (Brako et al., 2021; Dompreh et al., 2021; Oosterveer et al., 2014) examined the effects of sustainability certification programmes (such as the Roundtable on Sustainable Palm Oil) on palm oil production and on social dynamics, respectively. This is somewhat unsurprising, since it tracks broadly to patterns observed globally (Reiss-Woolever et al., 2021), and because uptake of certification schemes across Africa is generally low, possibly because African farmers face barriers to becoming certified that are not present or easier to overcome in other palm oil-producing regions such as Southeast Asia, where certification uptake is much higher. Further, most African palm oil is used and traded on the African continent rather than exported to Europe or the USA (Ordway et al., 2017), where retailers may be more likely to demand certification (RSPO Impact Report, 2016). Indeed, only 32,383 ha of oil palm in Africa (about 3 % of the total area estimate of closed-canopy oil palm) were RSPO-certified as of 2016, while in Indonesia and Malaysia alone the area of RSPO-certified oil palm was >2.30 Mha (about 12 % of the total area estimate of closed-canopy oil palm) (Descals et al., 2021; RSPO Impact Report, 2016). Co-occurrences between outcomes and social and government programmes that were not certification-specific were commoner. However, while the effects of these programmes on social dynamics were relatively well studied, we found that few studies have assessed their impacts on production or environmental conditions. As the purpose of these social and government programmes, such as zero deforestation pledges and the Clean Development Mechanism under the United Nations Framework Convention on Climate Change (UNFCCC) Kyoto Protocol, is to maximise palm oil production while mitigating adverse social and environmental impacts, future studies to assess their efficacy in oil palm settings in Africa are needed urgently.

A final potentially fruitful area for more research indicated by our co-occurrence analysis was the paucity of studies focussed on the impacts of oil palm cultivation on elections and land rights and land grabbing, despite increases in oil palm cultivation across Africa. Such studies are needed to quantify the extent of political influence that oil palm developers can have on local communities, and to protect the rights of indigenous and other local people as oil palm cultivation continues to expand across Africa.

4.2. The Sustainable Oil Palm in West Africa (SOPWA) Project: A whole-ecosystem approach to understanding the relative impacts of traditional and industrial approaches to oil palm cultivation in Liberia

Our new research programme in Liberia—the SOPWA Project, which uses oil palm as a model tree crop to investigate the impacts of tropical agricultural production in Africa—helps to address several knowledge gaps that were revealed by our systematic mapping. First, we are establishing baseline data on levels of biodiversity, functioning, and ecosystem processing in three African systems (forest, country palm, industrial oil palm). As Liberia retains the highest density of structurally intact Western Guinean lowland forest (Song et al., 2018), studying Liberia's forests will advance aims of protecting remaining intact forest areas and inform targets for initiatives to restore areas that are degraded.

Second, the SOPWA Project is the first to evaluate the whole-ecosystem impacts of oil palm cultivation in an African context. In this paper, we used canopy cover, ground vegetation cover, and soil temperature data as a case study to demonstrate the utility of the SOPWA Project's study design, showing that traditional and industrial approaches to oil palm cultivation lead to declines in canopy cover and ground vegetation cover and increases in soil temperature and soil temperature variability. These findings are unsurprising and mirror those from similar studies in Southeast Asia (Drescher et al., 2016;

Hardwick et al., 2015), although absolute values between our study and those in Southeast Asia varied somewhat (for instance, in their rainforest plots, Drescher et al. (2016) reported about 97.5 % canopy cover and Hardwick et al. (2015) reported soil temperatures ranging from about 22.8–23.9 °C; in comparison, in our rainforest plots, average canopy cover was lower, at 91.3 %, and soil temperatures were warmer, ranging from 24 to 26 °C). Our findings show clearly the SOPWA Project's ability to quantify the impacts of oil palm cultivation practises on ecological conditions. For country palm, cultivation practices include burning small areas of rainforest and planting of crops, which are farmed for one to two years before allowing the areas to regenerate (although regeneration may be only partial, depending on when the area is farmed again). For industrial oil palm, cultivation practices involve cutting-down rainforest and planting oil palm monocultures, which are harvested for an approximately twenty-five-year commercial cycle and managed intensively with chemical inputs and industrial machinery (Ashton-Butt et al., 2018; Global Forest Watch, 2014; Luke et al., 2019, 2020). It is likely that the changes in structural complexity (canopy cover, ground vegetation cover) and microclimate (soil temperature and soil temperature variability) are indicative of larger impacts of cultivation on biodiversity and ecosystem functioning (Barnes et al., 2014; Drescher et al., 2016), and we will investigate this in future SOPWA Project work. To date, the SOPWA Project has also surveyed vegetation structural complexity; the biodiversity of trees, understory plants, birds, bats, ground-dwelling mammals, spiders, and insects; and levels of ecosystem functioning including seed removal, ant scavenging activity, forest regeneration, and soil invertebrate feeding activity. We have specifically chosen these conditions and taxa because they also feature in seminal studies (e.g., Drescher et al., 2016; Ewers et al., 2011) that have investigated the ecological impacts of oil palm cultivation in Southeast Asia, and therefore provide a focus to compare the relative environmental impacts of palm oil production across native (i.e., Africa) and non-native (i.e., Southeast Asia and Latin America) regions. Further, they are aspects of the ecosystem that are likely to impact ecosystem services that influence the productivity and profitability of oil palm systems. In addition to our ecological surveys, the SOPWA Project is also assessing the impacts of cultivation on sociocultural factors. For instance, we have conducted ethnobotanical surveys with local plant specialists to understand the social, cultural, medicinal, spiritual, and economic value of understory plant species to local communities.

Third, whilst most oil palm-focussed research worldwide is concerned with industrial and – to a lesser extent – smallholder approaches to cultivation (Reiss-Woolever et al., 2021), the SOPWA Project is providing first insights into traditional "country palm" cultivation. This approach to oil palm cultivation is commonly practised across oil palm's native range, but the ecological value of the country palm system has not been quantified. Our case study on canopy cover, ground vegetation cover, and soil temperature data indicated that country palm systems sit somewhere in between forest and industrial oil palm systems, in terms of their ecological value. For instance, we found that soil temperatures in industrial oil palm were consistently hotter than in rainforest, regardless of time of day. In comparison, soil temperatures in country palm and rainforest differed only during the day and, at the middle of the day, temperatures in country palm were cooler than in industrial oil palm. These findings – and those from understory management experiments in oil palm plantations in Southeast Asia (Luke et al., 2020) – indicate that the middle of the day is when habitat changes have the greatest impact on ecosystems through influences in microclimate. With ever-increasing temperatures owing to climate changes, these cooler systems could provide greater conservation benefits to species with poor buffering abilities. Further production-focussed studies are needed to assess the relative ecological value of country palm and industrial oil palm systems, accounting for the volume of palm oil that each system produces to identify the best approaches that balance ecological impact and yield (Stichnothe and Schuchardt, 2011).

Importantly, the SOPWA Project demonstrates that large-scale, field-based studies in remote areas of the tropics are possible, especially when grounded in collaboration (Luke et al., 2020). Our new programme is a full collaboration between international academics and palm oil industry partners Golden Veroleum Liberia, with project support provided by local communities in the study area and the Government of Liberia's Forestry Development Authority. Our collaborative relationships are set-up such that research progress and interpretation of findings is free from influence, and findings will be fed-back to all project partners to encourage changes in land management and policymaking in both top-down and bottom-up directions, ultimately ensuring the development of approaches that more fully take sustainability into account.

5. Conclusions and future directions for research

Our systematic mapping exercise demonstrated that oil palm-based research in Africa is increasing, but that several key research gaps remain that need to be addressed. Our new research programme in Liberia—the SOPWA Project—was conceived to help to address some of these gaps, including shedding light on the relative ecological impacts of traditional and industrial approaches to oil palm cultivation. Our case study on canopy cover, ground vegetation cover, and soil temperature data indicated that West African rainforests are ecologically distinct from oil palm systems, but also that traditional and industrial oil palm systems can be ecologically complex and have differing ecological impacts. Over time, we will publish multi-taxa and sociocultural findings, to more fully quantify the impacts of these alternative cultivation practices and their potential effects on a wider range of ecosystem services. We hope that by highlighting the SOPWA Project approach and study design, we will encourage future similar projects in the West Africa region and more collaborations within the SOPWA Project itself.

This paper is a foundation for forthcoming SOPWA Project research. The utility of our study design is that—now that our monitoring plots are established—almost any aspect of the ecosystem can be studied within them. We encourage researchers who would like to collaborate to get in touch, to advance our goal of making tropical agricultural development on the African continent more sustainable.

Ethical approval

Ethical approval for interviews with farmers (Supplementary Table 4) was obtained from the Cambridge Psychology Research Ethics Committee (Application number: PRE.2020.004).

CRediT authorship contribution statement

Michael D. Pashkevich: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Cicely A.M. Marshall:** Writing – review & editing, Resources, Methodology, Data curation, Conceptualization, Funding acquisition, Project administration. **Valentine J. Reiss-Woolever:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jean-Pierre Caliman:** Writing – review & editing, Conceptualization. **Julia Drewer:** Writing – review & editing, Data curation. **Becky Heath:** Writing – review & editing, Data curation, Conceptualization. **Matthew T. Hendren:** Writing – review & editing, Methodology, Data curation. **Ari Saputra:** Writing – review & editing, Data curation. **Jake Stone:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jonathan H. Timperley:** Writing – review & editing, Methodology, Data curation, Conceptualization. **William Draper:** Writing – review & editing, Conceptualization. **Abednego Gbarway:** Writing – review & editing, Project administration. **Bility Geninyan:** Writing – review & editing, Project administration, Data curation, Conceptualization. **Blamah Goll:** Writing – review & editing, Project administration. **Marshall Guahn:** Writing – review & editing, Data curation. **Andrew N. Gweh:** Writing –

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Declaration of competing interest

Co-authors with a Forestry Development Authority (FDA), Golden Veroleum Liberia (GVL), and Sinar Mas Agro Resources and Technology Research Institute (SMARTRI) affiliation were employed by their respective institutes while research was conducted. University of Cambridge retains all intellectual property rights and data-use for all researchers involved in this study. This research is therefore a collaboration between all affiliated parties.

Data availability

Data are available on the University of Cambridge Online Digital Repository: https://doi.org/10.17863/CAM.107163.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171850.

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