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Potential for low-emissions oil palm production in Indonesia: insights from spatiotemporal dynamics

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Abstract

Rising global demand for palm oil has created environmental pressures related to deforestation, burning, and peat exploitation, which in turn drives increased greenhouse gas (GHG) emissions. GHG emissions in oil palm (OP) production are known to vary spatially. However, temporal changes across contrasting management and soil types, are less well studied. This paper quantifies spatiotemporal GHG emissions across contrasting regions, management types, and soil types for the period 1990–2019 to assess the potential for reducing emission. The study focusses on Indonesia, as the biggest producer of OP, and in particular on the North Sumatra and Riau provinces, where OP is intensively produced. GHG inventories in 5 year time steps were constructed to investigate the change in drivers of emissions using spatial data, resampled to a 500 m grid. Total GHG emissions were found to have increased in both regions due to expanding OP production. However, results show a reduction in emissions flux from 1.98 to 1.15 Ton C_{eq}. ha^{-1} yr^{-1} in North Sumatra and 9.63–2.67 Ton C_{eq}. ha^{-1} yr^{-1} in Riau over the study period. This reduced flux was linked to the decreased deforestation and burning activities, together with increased biomass increment from lower carbon stock area conversion to OP. In both provinces, smallholder plantations emitted fewer emissions than industrial ones, and production on organic soils resulted in consistently higher emissions than on mineral soils. In North Sumatra, emissions under all management and soil types were found to decrease. In Riau, however, GHG emissions on organic soils regardless of management types, remained high. Our findings emphasise that potential for low-emissions OP production is attainable by reducing emissions per unit area through an improved understanding of GHG emissions spatiotemporal variability and their drivers. These contribute to reinforcing ongoing government regulations and guiding the industry towards low-emission OP productions.

1. Introduction

Oil palm (OP) production contributed 2.3% of global anthropogenic greenhouse gas (GHG) emissions in 2020, primarily through land-use change (Van Straaten *et al* 2015, Rahman *et al* 2018, Pendrill *et al* 2019, Meijaard *et al* 2020) and drained peatland emissions (Page *et al* 2011, Hooijer *et al* 2012, Cooper *et al* 2020). As the global demand for palm oil is predicted to increase by 0.5%–3% per year (Murphy *et al* 2021), there is growing pressure on Indonesia, responsible for over 50% of the world's palm oil production, to produce OP in a more sustainable way.

A series of national government regulations, sustainable palm oil certification initiatives, and international commitments aimed at preserving pristine forests, protecting the environment, and reducing GHG emissions from deforestation, have been established (Carlson *et al* 2018, Oosterveer 2020, Purnomo *et al* 2020). These have led to a reduction in deforestation associated with OP expansion (Austin *et al* 2019, Gaveau *et al* 2022, Parker 2022). However, their impact on GHG emissions dynamics have not been explored.

GHG emissions from OP production vary spatially (Carlson *et al* 2013, Lam *et al* 2019) from 0.44 to 40.91 Ton C_{eq}. ha^{-1} yr^{-1} across different systems, locations and soil types (Silalertruksa *et al* 2017, Alcock *et al* 2022), with emissions being higher on drained peat soils (Hooijer *et al* 2010, Cooper *et al* 2020) and from direct forest conversion (Pendrill *et al* 2019, Xu *et al* 2022). However, previous studies have not explored how emissions vary across contrasting management and soil types and have examined only major changes in the 20 years after C biomass and soil organic carbon (SOC) equilibria (Silalertruksa *et al* 2017, Lam *et al* 2019, Alcock *et al* 2022, Friedlingstein *et al* 2022). As a result, there is a knowledge gap over changes in GHG emissions from OP production and the contribution of different drivers to emissions (e.g. land use change, fire and burning, and peatland exploitation).

To address this gap, this study explores changing spatio-temporal patterns of GHG emissions and their intermediate drivers across contrasting regions, management regimes, and soils. It aims to provide insights on the spatiotemporal dynamics of emissions and their intermediate drivers to strengthen government policies and guide the OP industry to achieve low-emission OP production. A robust policy commitment and continued implementation of sustainable practices are crucial for protecting the environment and reducing emissions.

2. Methods

A GHG inventory (IPCC 2006, 2019) consisting of 5 year periods between 1990 and 2019 was used to quantify the spatiotemporal GHG emissions and identify intermediate drivers in two contrasting OP production regions in Indonesia (figure 1). It examined land use changes to OP production in the periods 1990–1996, 1996–2000, 2000–2006, 2006–2011, 2011–2015, 2015–2017, and 2015–2019. These periods were selected to match the availability of data as described below. The overall framework for the analysis is shown in figure 2.

2.1. Site characteristics

The study area was OP plantations in North Sumatra and Riau province, Indonesia. North Sumatra is situated between 1°–4° N and 98°–100° E, covering area of 7.29 Mha and Riau stretches 01°31–02°25° S and 100°–105° E, with an area of 8.70 Mha. Both provinces have the largest OP plantations in the country, with Riau covering 2.40 Mha and North Sumatra covering 1.37 Mha. In Riau province, 60.2% of the OP plantations are on organic soils and 39.8% on mineral soils (Tubiello *et al* 2016, Descals *et al* 2021). In North Sumatra, the majority of the OP plantations (0.97 Mha) are located on mineral soils (71.26%), while 28.73% are located on organic soils. Organic soils are composed primarily of organic material originating from recent plant remnants (Kazemian 2018). Mineral soils contain less SOC, from 1% to 6%, while organic soils contain higher SOC, from 12% to 18% (Troeh and Thompson 2005). Organic soils with more than 75% SOC are classified as peat soils (Kazemian 2018). Higher SOC on organic soils can potentially contribute to emissions as a result of land drainage and management.

In terms of management, OP plantations are predominantly owned by industrial-state companies in North Sumatra (60%), with 40% owned by smallholders, and in Riau 35% are industrial-private owned and 65% by smallholders. In this context, an industrial OP either state-owned or private, refers to a large OP plantation that has complete infrastructure such as roads, drainages, labour system, housing, and mills, with planting, maintenance, harvesting, transportation, and processing managed professionally. In contrast, smallholder OP plantations tend to be managed and owned by individual farmers, do not generally exceed 25 ha, and are managed according to the capital available to the farmer. The life cycle of an OP plantation is between 25 to 30 years. Many industrial OP plantations in North Sumatra province were established in the 1980s, with most of the plantations replanted and now in their second cycle. In Riau province, the establishment of OP plantations began on a large scale in the 2000s. They are still in the first cycle and due to be replanted soon.

2.2. Datasets description

The data used in this study are described in full in table S1. It consists of land use/cover (LULC) maps for the period 1990–2015, OP plantation distribution maps between 1995 and 2017 (Danylo *et al* 2021), smallholder and industrial OP plantations distribution maps from 2019 (Descals *et al* 2021), carbon (C) biomass burning emissions between 1997 and 2016 from the Global Fire Emissions Database (GFED, Werf *et al* 2017), C and nitrogen in nitrous oxide (N_2O–N) emissions from drained organic soils (Tubiello *et al* 2016, Food and Agriculture Organization of the United Nations 2018), and 2019 national average nitrogen (N) fertilizer and empty fruit bunch compost applications (Monzon *et al* 2021). For ease of computation and analysis consistency across scales, data were resampled and aligned to 500 m grids using area-weighted interpolation for vector area data and bilinear interpolation for any gridded data.

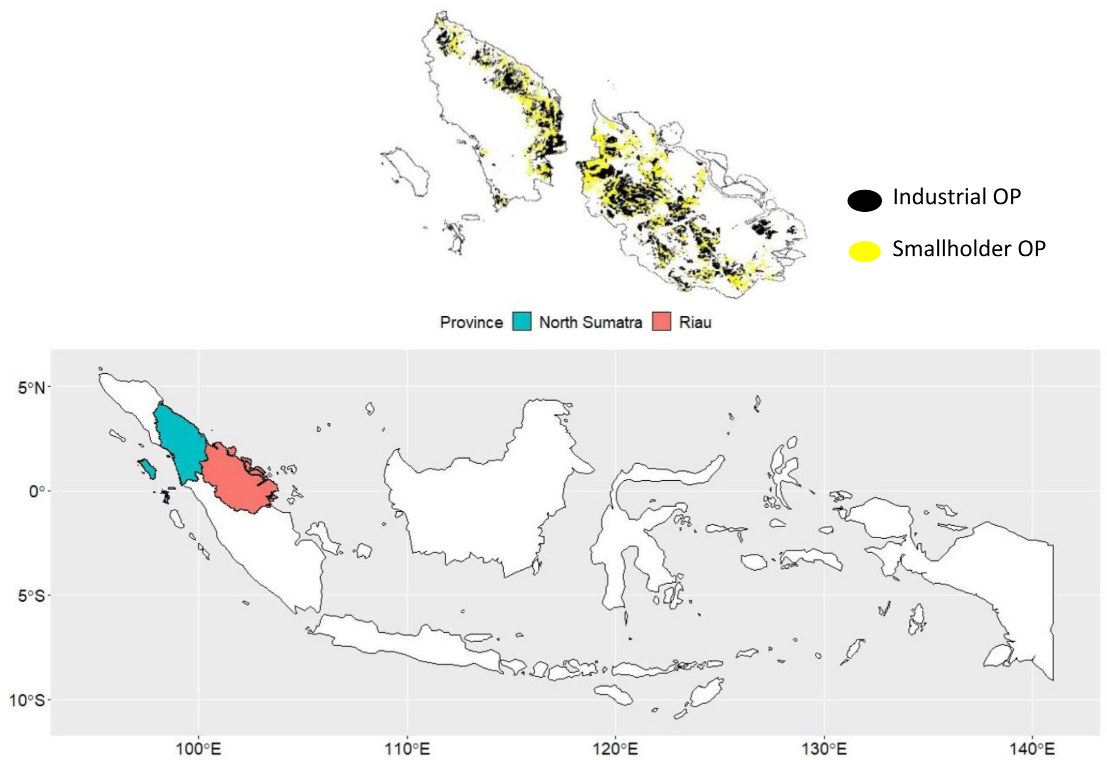

Figure 1. The study area (bottom) and OP plantations (top) in North Sumatra (left) and Riau province (right), separated for visual clarity. Source: Descals *et al* (2021).

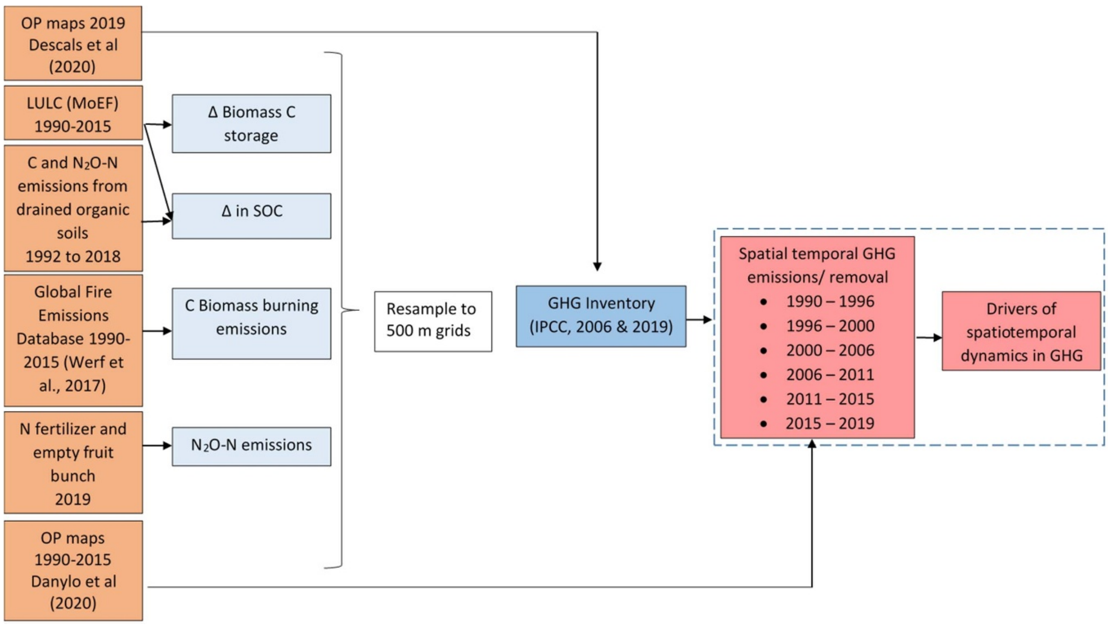

Figure 2. Workflow, spatiotemporal GHG emissions, and associated drivers.

LULC vector data were obtained from the Ministry of Environment and Forestry, Indonesia at 1:25 000 scale (Tosiani 2020). The datasets included 23 categories such as forests, plantations, scrubland, agriculture, rice fields, etc. To assess the distribution of OP plantations, two datasets were used. The first covered the period from 1990 to 2015 and provided information on the extent and age of productive OP in Indonesia, Malaysia, and Thailand at a 30 m grid resolution (Danylo *et al* 2021). The second reflected global OP distribution in 2019 at a 10 m grid resolution classified as industrial or smallholder closed-canopy OP plantations (Descals *et al* 2021).

C biomass burning emissions from the OP plantations were derived from monthly C emissions (g Cm^{-2}) of GFED for 1997–2016 at 0.25° grid resolution (van der Werf *et al* 2017). The data were prepared by converting the gridded raster data into vector polygons and adjusting the unit of measurement. Emissions from drained organic soils were retrieved from global datasets for C and N_2O–N from 1992 to 2018 at 1 km resolution. C and N_2O–N emissions were estimated using the Tier 1 methodology based on the presence of histosols as a proxy for organic soils (IPCC 2006, Food and Agriculture Organization of the United Nations 2018).

2.3. Spatiotemporal GHG emissions/removals

GHG emissions/removals (Ton $C_{eq.}$ ha^{-1} yr^{-1}), ΔGHG, represent the C change in biomass stock, SOC, biomass burning, and management (IPCC 2006, 2019) as shown on the equation (1). Dead organic matter was not included due to limited information and its insignificant contribution (Pardon *et al* 2016). ΔGHG is defined as follows:

$$\Delta GHG = \Delta C_{luc} + \Delta C_{soc} - \Delta C_b - \Delta C_m \ldots \quad (1)$$

where ΔC_{luc} is the change in biomass C stock in land use change converted to plantation and remaining plantation, ΔC_{soc} is the change in SOC due to land use change and emissions in drained organic soils, ΔC_b is C emissions from biomass burning activity and ΔC_m is the N_2O–N emissions from fertilizer application and organic amendment, all in Ton C_{eq}. ha^{-1} yr^{-1}.

The temporal analysis was not in precise 5 year sequences 1990–2019 due to missing datasets for LULC in some years. As a result the analysis periods were 1990–1996, 1996–2000, 2000–2006, 2006–2011, 2011–2015, and 2015–2019. The 2019 OP distribution map by Descals *et al* (2021) was the primary dataset for distinguishing smallholder and industrial OP plantations and the maps of Danylo *et al* (2021) was then used to filter GHG for each ∼5 year period. For instance, emissions from 1990 to 1996 were determined based on OP maps from 1984 to 1996, and emissions from 1996 to 2000 relied on maps from 1984 to 2000 and so on.

3. Results

3.1. Spatiotemporal dynamics of GHG emissions in OP productions

The spatial distributions of GHG emissions from OP plantations were calculated over 5 year time steps (figure 3). These aligned with the increases in OP areas in both provinces and identified specific hotspot areas with high emissions, as well as locales of carbon removal.

Overall, Riau province exhibited higher emissions per unit area compared to North Sumatra. In Riau province, most of the area emitted 3.76–13.73 Ton $C_{eq.}$ ha^{-1} yr^{-1} (0.21 Mha) in the early period (1990–1996), which declined to 1.19–5.71 Ton $C_{eq.}$ ha^{-1} yr^{-1} (1.19 Mha) in the late period (2015–2019). The regions with high GHG emissions expanded in area from 0.10 Mha to 0.60 Mha. A few C removal areas only covered 0.004 Mha in 1990–1996 but increased to 0.22 Mha in 2015–2019.

In North Sumatra, most areas exhibited GHG emissions from 1.15 to 3.5 Ton $C_{eq.}$ ha^{-1} yr^{-1} (0.17 Mha) in 1990–1996. While during the later period (2015–2019), it ranged from −0.09 (removals) to 1.67 (emissions) Ton $C_{eq.}$ ha^{-1} yr^{-1}. C removal areas were detected across the region, spreading increasingly from 0.05 Mha in 1990–1996 to 0.47 Mha in 2015–2019. A few high emissions areas (>5.20 Ton $C_{eq.}$ ha^{-1} yr^{-1}) were identified in the south–east part along the border with Riau province.

The GHG emissions flux in OP plantations under different managements and soil types in both provinces are shown in figure 4. They indicate a declining trend. Overall, the median value decreased from 1.98 to 21.15 Ton $C_{eq.}$ ha^{-1} yr^{-1} in North Sumatra and from 9.63 to 2.68 Ton $C_{eq.}$ ha^{-1} yr^{-1} in Riau. In both provinces, smallholder plantations produced less GHG emissions per unit area than industrial plantations, while emissions on organic soils were always higher than on mineral soils. In both provinces, GHG emissions from drained organic soils under industrial management were higher than under smallholder plantations (*t*-value for North Sumatra = 33.1–117.6, *t*-value for Riau = 14.5–60.4, p value < 0.001 in both cases), with this potentially resulting on mineral soils under smallholder management becoming GHG sinks after 2000.

In North Sumatra, GHG emission flux from industrial OP plantations on organic soils are higher in magnitude between 1990 and 2000 before decreasing after 2000. In Riau, this declining trend was detected only on mineral soils, while emissions on organic soils both in smallholder and industrial remained high.

Although GHG emissions per unit area reduced in both regions, total emissions still increased due to expansions in OP production area, from 0.91 to 1.74 M Ton C_{eq}. ha^{-1} yr^{-1} in North Sumatra and from 4.04 to 8.84 M Ton C_{eq}. ha^{-1} yr^{-1} in Riau (figure 5). However, total C_{eq} emissions in 2011–2015 were lower than 2000–2006 and 2006–2011 despite OP cultivation being greater in these periods, contributing to reduced emissions flux.

3.2. Drivers of spatiotemporal dynamics in GHG emissions in OP productions

The contributions of intermediate drivers of GHG emissions in OP productions were analysed and were shown to decrease GHG emission flux, as illustrated by the changes in magnitude of C sources and sinks

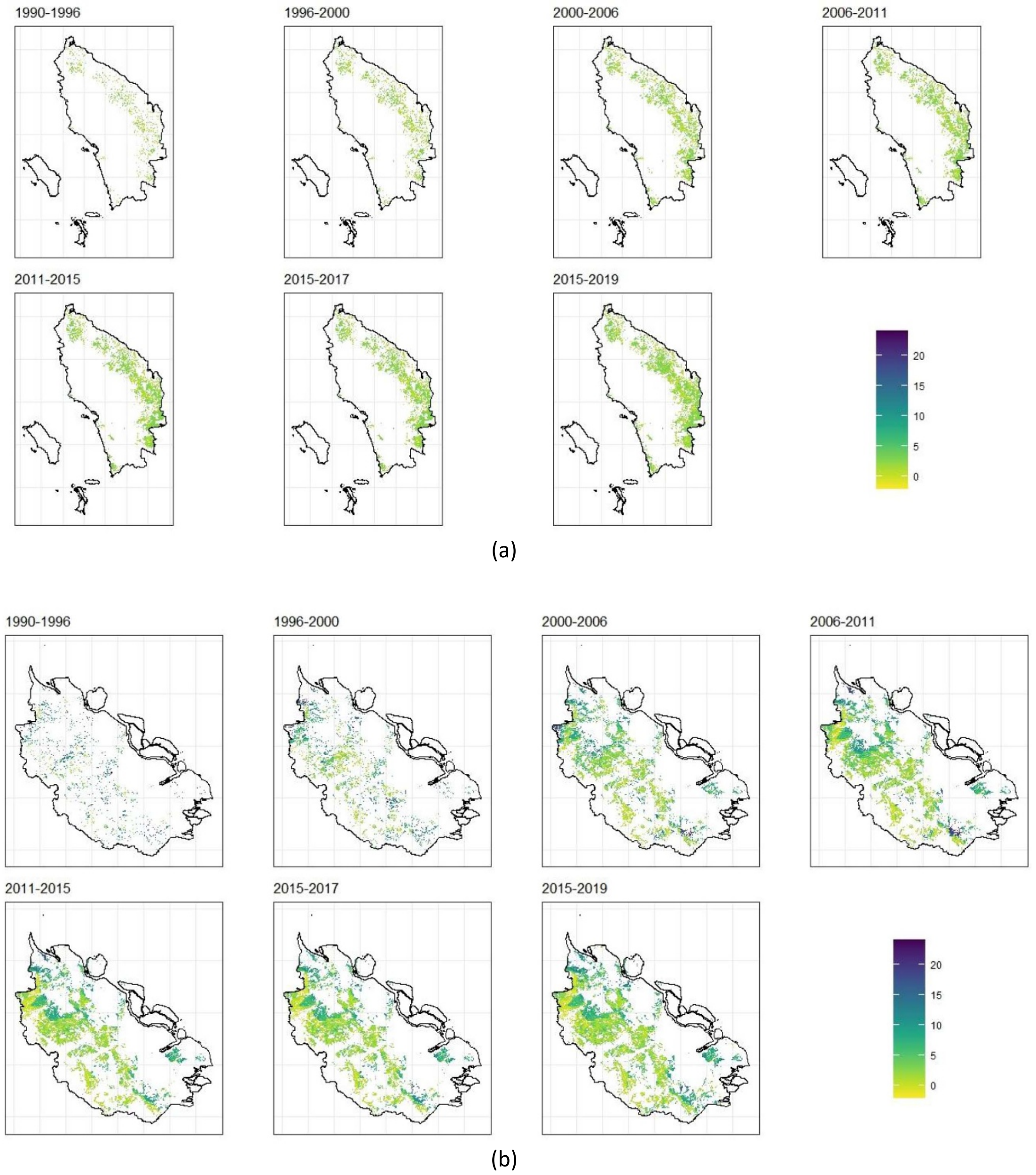

Figure 3. Spatiotemporal distributions of GHG emissions/removals (Ton C eq.ha^{-1} yr^{-1}) within OP plantations from 1990 to 2019 in (a) North Sumatra and (b) Riau province.

in figure 6. In North Sumatra, soil N_2O–N emissions from fertilizer applications were consistently the highest contributor of GHG emissions, while changes in burning emissions and SOC driven by land use change and drained organic soils declined overall. In Riau province, the most important emissions sources were burning and SOC changes in the early period 1990–2000. The contribution of burning emissions to GHG were higher before 2011 and then reduced, whilst the contribution of N_2O–N emissions and changes in SOC were consistently high over the same period.

In both provinces, the contribution of biomass C to net GHG shifted from a loss between 1990 and 1996 to a gain between 1996 and 2019. The decline in burning emissions can be attributed to the shift away from burning for OP land expansion, with some emissions remaining due to natural fire, particularly in Riau province.

The reduction in GHG emissions from biomass C storage and SOC change was strongly affected by shifts in land use towards OP plantations. Land use conversion analysis (figures 7 and 8) revealed contrasting patterns in land use conversion to OP plantation across both provinces, according to soil types. In North Sumatra, 60%–80% of OP plantations were established in old plantations (figure 7). From 1990–2000–2011–2019, deforestation associated with OP

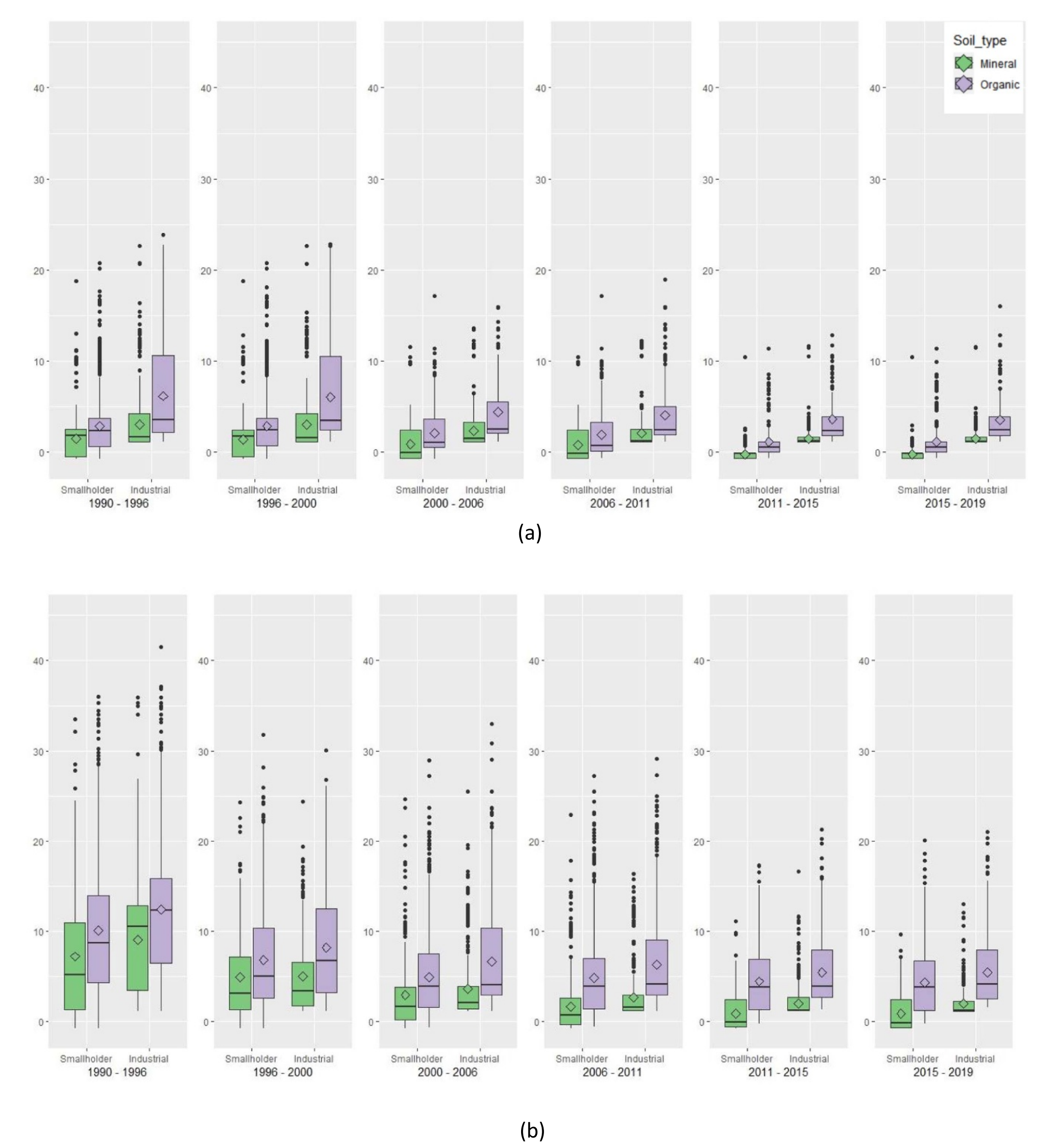

Figure 4. GHG emissions/ removals (Ton C eq. ha^{-1} yr^{-1}) of OP plantations in contrasting soil and management types between 1990 and 2019 (left to right) in (a) North Sumatra and (b) Riau.

decreased from 16.62% to 0.54% on organic soils and 13.53%–0.30% on mineral soils, with an associated increase in conversion from cropland (6%–30% on average).

In Riau province, 54.44% OP plantations on organic soils and 36.67% on mineral soils were directly converted from forest during 1990–2000, decreasing to 0.40% and 1.15%, respectively in 2011–2019. During 2000–2011, the majority OP plantations on both organic (89.18%) and mineral (91.19%) soils were established in old plantations. Subsequently, OP conversion from cropland on organic and mineral soils increased on average from 7% to 20%.

4. Discussion

4.1. Temporal changes in GHG emissions of OP production

Previous studies on GHG emissions in OP plantations have primarily focused on either short-term measurements (Hooijer *et al* 2010, Dariah *et al* 2014, Rusch *et al* 2020, Agusta *et al* 2022) or GHG inventories conducted in 20 year time steps (Silalertruksa *et al* 2017, Lam *et al* 2019, Alcock *et al* 2022), overlooking finer grained temporal dynamics in GHG emissions and their drivers. This study seeks to address this gap and links the temporal changes in GHG emissions to reduced forest conversion, aligning with recent work

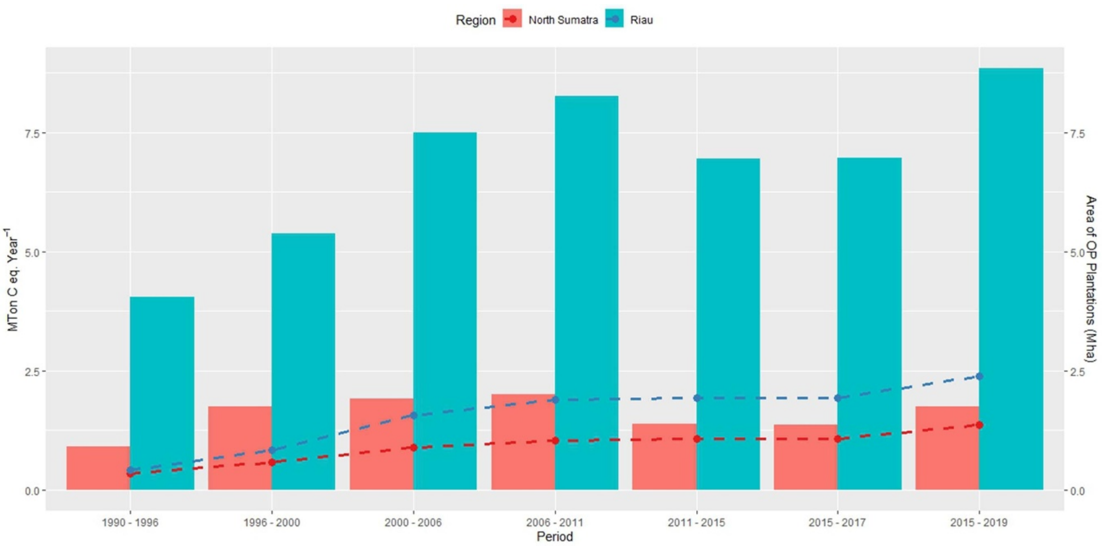

Figure 5. Total GHG emissions and OP expansion in North Sumatra and Riau between 1990 and 2019.

that has identified declining deforestation as a potential driver of reduced GHG emissions (Ramdani *et al* 2013, Austin *et al* 2019, Gaveau *et al* 2019, Meijaard *et al* 2020, Parker 2022).

OP plantations were initially established around in the early 1980s together with timber plantations to enhance the productivity of logged and degraded land forests which had succeeded to secondary forest and scrubland (Barani *et al* 2021). National-level OP plantations expanded gradually from 1990 to 2000 and then experienced rapid growth (Rehman 2015, Austin *et al* 2019, Gaveau *et al* 2019). On a national level, OP plantations covered 0.29 Mha in 1980, of which 67.7% were state-owned plantations, and increased from 2000 to 2020 (from 4.10 Mha to 14.70 Mha), mainly privately owned plantations (Direktorat Jenderal Perkebunan Indonesia 2018, Barani *et al* 2021).

In relation to this expansion, this study showed that the majority of direct conversion from forests occurred before 2000 and then decreased afterwards. This finding is reinforced by other work that has shown that recent OP plantation expansion has primarily originated from previous old plantations (rubber, cocoa, tea, etc) and from scrubland (Rehman *et al* 2015, Santosa *et al* 2020, Parker 2022) rather than from primary and secondary forests. This decline in deforestation can be attributed to a series of national government regulations, the introduction of sustainable OP certifications, and international commitments aimed at preserving pristine forests, protecting the environment, and reducing GHG emissions from deforestation (Tata *et al* 2014, Oosterveer 2020, Purnomo *et al* 2020).

Sustainable OP certifications (ISPO since 2015 and RSPO since 2017) also promote management practices that avoid burning (Noojipady *et al* 2017), decreasing burning activities in OP plantations. However, it is noteworthy that only 35.29% of OP plantations were certified under ISPO in 2020, and 59% under RSPO in 2016 (RSPO 2016).

The enforcement of certifications could significantly enhance the sustainability of OP production and contribute to reducing GHG emissions from burning and deforestation (Carlson *et al* 2018, Vadrevu *et al* 2019). Despite efforts to promote zero burning in OP plantations, the occurrence of El Niño, together with the presence of natural fire hotspots, has led to fires, particularly in peat areas (Noojipady *et al* 2017, Nurdiati *et al* 2022, Hayasaka 2023). Significant fire incidents were observed in 1997, 2006, 2015, and 2019 (Wang *et al* 2004, Noojipady *et al* 2017), which supports our findings of high burning emissions in these periods. Policy and practice should acknowledge these drivers by ensuring adequate water levels are maintained in OP plantations to avoid irreversible drying conditions, which are known to exacerbate such fires (Imanudin *et al* 2018, Sahari *et al* 2020, Barani *et al* 2021).

This paper quantifies the spatiotemporal dynamics of GHG emissions in OP plantations and attributes them to intermediate drivers such as land use change and burning. Decreased burning and OP conversion related deforestation have resulted in reduced GHG emissions flux over the period of 1990–2019. These results are consistent with other work that has reported a decline in deforestation associated with OP, as well as increases in sustainable palm oil certifications in Indonesia and Malaysia over the last 10 years (Carlson *et al* 2018). The temporal dynamics are also consistent with trends in annual CO_2 emissions associated with land use change in Indonesia, which have

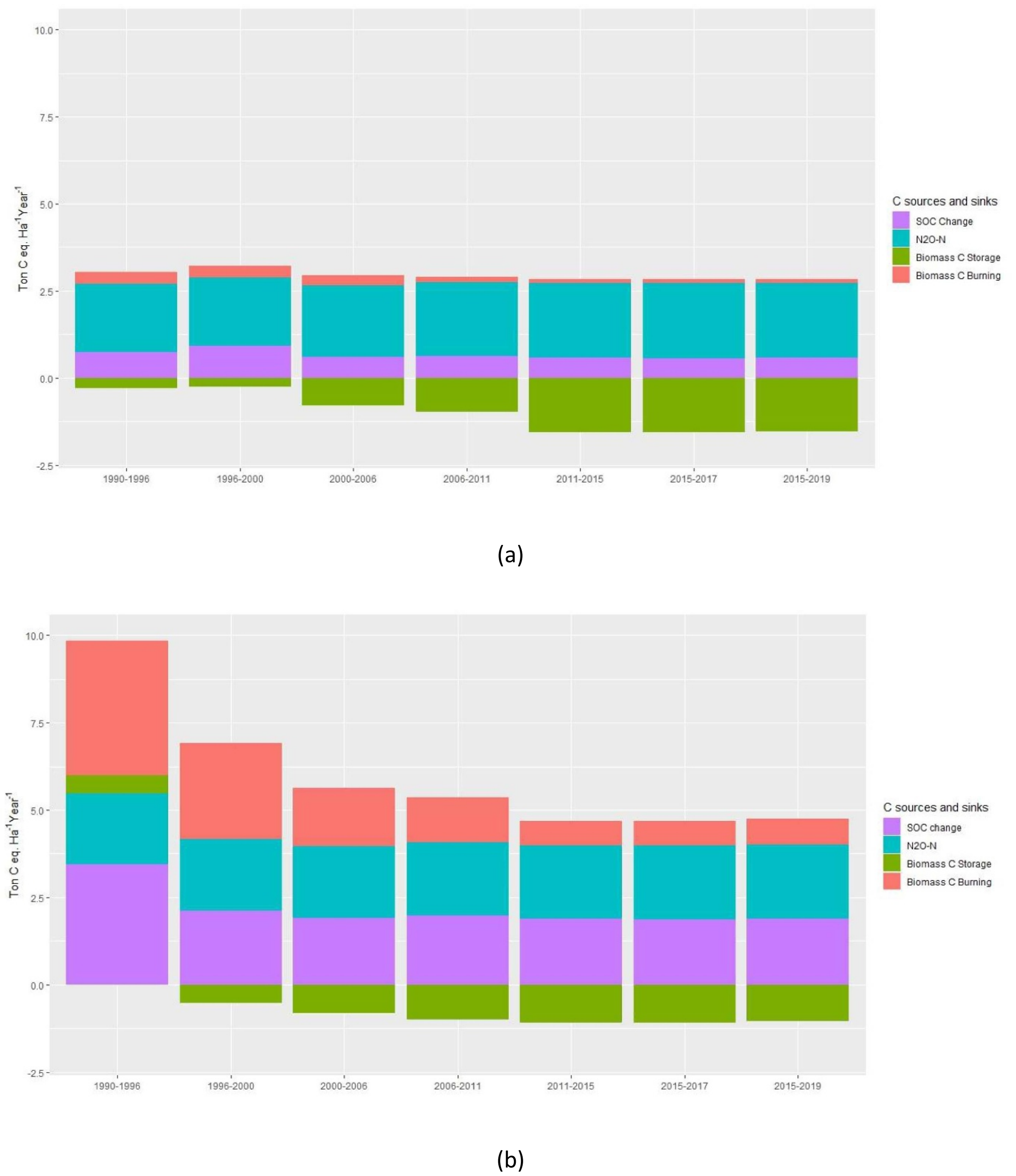

Figure 6. The change in magnitude of C sources and sinks (Ton C eq.ha^{-1} yr^{-1}) in OP plantations from 1990 to 2019 in (a) North Sumatra and (b) Riau Province.

decreased between 1990 and 2019, with a spike occurring in 1996 (Friedlingstein *et al* 2022).

Although GHG emissions flux reduced over the period, total emissions were found to increase in both provinces due to the extensive expansion of OP plantations over the period (Meijaard *et al* 2020). However, reduced emissions per unit area has potential to translate to lower overall emissions and offers a promising pathway towards reducing emissions in the worldwide palm oil supply. Low emission OP production, with low emissions per unit area, is achievable by strengthening and enforcing regulations and sustainable OP certifications, with a focus on preventing deforestation and burning in OP cultivations. Ongoing monitoring is imperative, particularly for smallholder OP plantations where the risk of encroachment into forest and peatland areas is greater (Xu *et al* 2022, Zhao *et al* 2022).

Monitoring trends in GHG emission flux of OP is crucial to support the ambition of low emission OP productions and this study has shown that this can be achieved by undertaking spatiotemporal GHG inventories using global datasets. However, uncertainties are present, and analyses of these are needed to provide a comprehensive understanding of the reliability and limitations, which will facilitate a more informed decision-making process, ultimately aiming to lower emissions from OP productions.

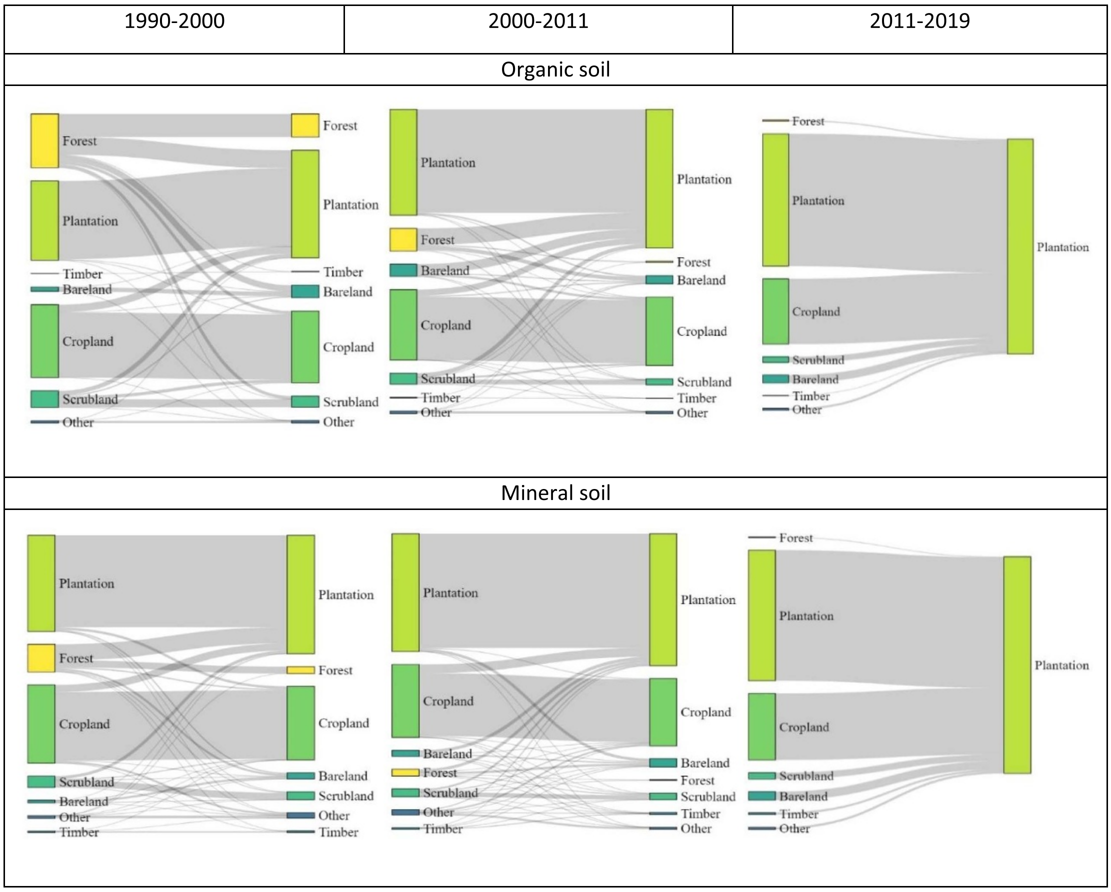

Figure 7. Land use conversion to OP plantation from 1990 to 2019 in North Sumatra.

4.2. Geographically-based agronomic improvement for reduced emissions in OP productions

This study showed that OP production related GHG emissions varied significantly. Areas of high emissions and C removal were detected, consistent with findings from other research (Lam *et al* 2019, Alcock *et al* 2022). Land use change and burning emissions estimates have been found to contribute significantly to discrepancies in emissions (van der Werf *et al* 2017, Carlson *et al* 2018).

This case study in North Sumatra and Riau showcased different production scenarios giving rise to low and high emissions. Riau province was found to have higher emissions compared to North Sumatra, similar to Lam *et al* (2019), who placed OP in Riau as the 3rd highest region in emissions nationally, after North and South Kalimantan.

Industrial plantations on drained organic soils had higher GHG emissions compared to smallholder plantations on mineral soils, in both provinces. This correlates with other studies (Cooper *et al* 2020, Alcock *et al* 2022). The reduction of forest conversion and burning emissions significantly contributed to the reduced GHG emissions flux on mineral and organic soils in North Sumatra. However, the ongoing expansion of OP plantations in Riau on organic soils elevated emissions from drained organic soils, while emission flux from mineral soils decreased.

Spatial analysis revealed hotspots of high GHG emissions, as well as sink regions which have significant potential for carbon removals. This highlights the need for approaches that account for spatiotemporal variability when mitigating GHG in OP production. Strategies aimed at achieving more sustainable, low-emissions OP production, such as avoiding forest conversion and peat areas (Afriyanti *et al* 2019, Lam *et al* 2019, Purnomo *et al* 2020, Meijide *et al* 2021), as well as expanding to lower carbon stock areas (Quezada *et al* 2019, Monzon *et al* 2021) are crucial to ensure the success of current policies, particularly for high emissions areas such as Riau, North Kalimantan, and South Kalimantan.

In low emissions areas such as North Sumatra, further agronomic improvement can be implemented to expand the low emissions area as well as to create areas for C removal. Agronomic improvements for emissions reduction include enhancing fertilizer application efficiency, using cover crops, developing disease-resistant cultivars (Khatun *et al* 2017), integrating inorganic and organic fertilizers (Foong *et al* 2019), optimizing timing and dosage

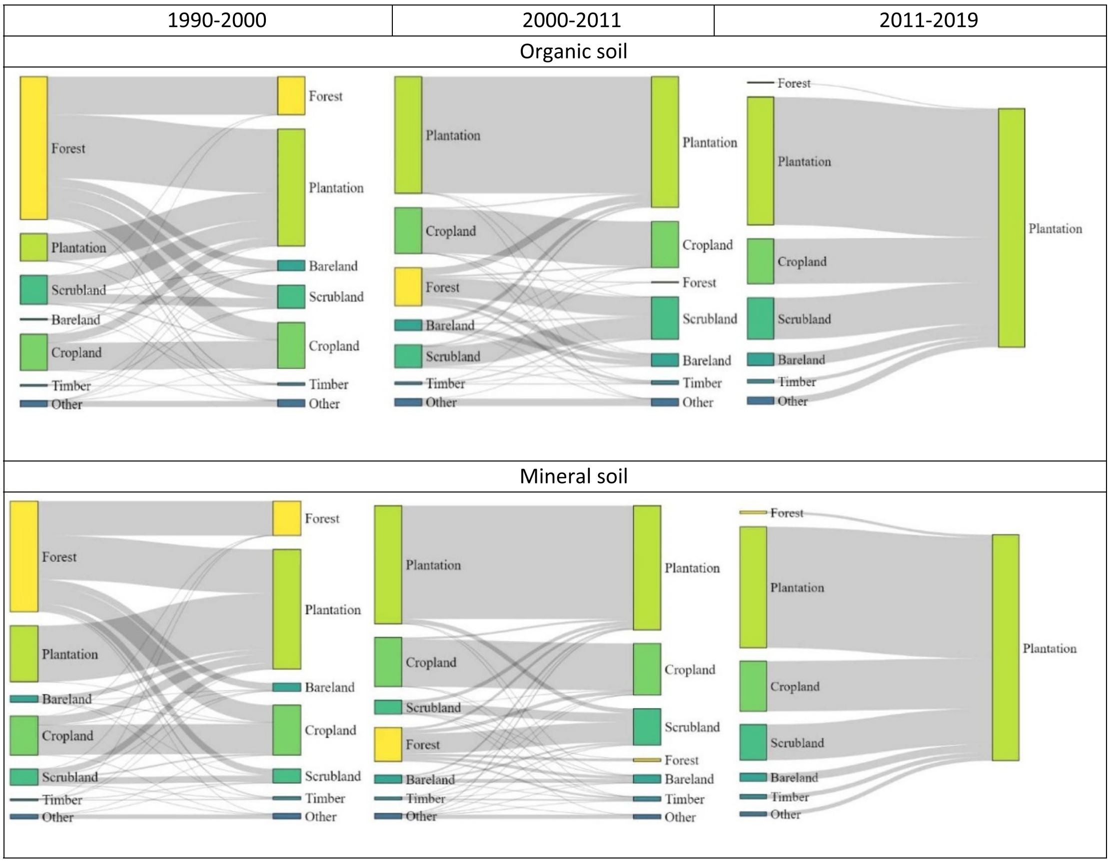

Figure 8. Land use conversion to OP plantation from 1990 to 2019 in Riau.

of fertilization, employing enriched mulch (Rahman *et al* 2019), enhancing SOC through best management practices (Rahman *et al* 2021), and adopting regenerative agriculture with intercropping and cover crops (Khasanah *et al* 2020). Land protection scenarios and geographical agronomic improvements in OP productions have the capacity to result in substantial reductions in global anthropogenic emissions. Further research to examine agronomic improvements for reducing emissions in OP productions can be explored through crop modelling.

5. Conclusions

Our study examined the spatiotemporal dynamics of GHG emissions using 5 year time steps during 1990–2019, revealing potential for low-emissions in OP productions in the two most productive OP regions in Indonesia. Results show a reduced emissions flux in both regions could be attributed to decreases in deforestation and burning activities, together with increases in conversion to OP from lower carbon stock areas.

The study confirms that GHG emissions in OP production exhibit variation across regions, management, and soil types. OP production in Riau province consistently emitted higher GHG compared to North Sumatra. Extensive forest conversion and burning led to high emissions in the beginning of OP establishment in Riau. In both provinces, smallholder plantations emitted fewer emissions. The ongoing large-scale OP cultivation on organic soils in this region continues to contribute to high GHG emissions. Moreover, the study identifies specific hotspot areas characterised by the highest emissions, as well as regions with potential for effectively removing carbon.

Our findings emphasise that potential for low-emissions OP production is attainable by reducing emissions per unit area through an improved understanding of the spatiotemporal variability of GHG emissions and their drivers. However, any strategies for sustainable OP production must also involve ongoing regulation enforcement and certification, alongside continued the promotion of best management practices. The exploration of geographically adapted agronomic improvement scenarios will also support mitigation strategies. Further research is required to investigate spatially-targeted agronomic improvements that build on these findings to deliver low-emissions OP production. Crop modelling is a promising tool in this regard, which would also facilitate analysis of uncertainties across both models and data.

Data availability statement

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

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