Journal of Environmental Management 344 (2023) 118505

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Deforestation, certification, and transnational palm oil supply chains: Linking Guatemala to global consumer markets

Calli P. VanderWilde [a,*], Joshua P. Newell [a], Dimitrios Gounaridis [a], Benjamin P. Goldstein [b]

[a] University of Michigan School for Environment and Sustainability, 440 Church Street, Ann Arbor, MI, 48109, USA
[b] McGill University, Department of Bioresource Engineering, 21111 Lakeshore Road, Ste-Anne-de-Bellevue, QC, H9X 3V9, Canada

ARTICLE INFO

Keywords:
Palm oil
Guatemala
Certification
Supply chain risk
Deforestation
Governance

ABSTRACT

Although causal links between tropical deforestation and palm oil are well established, linking this land use change to where the palm oil is actually consumed remains a distinct challenge and research gap. Supply chains are notoriously difficult to track back to their origin (i.e., the 'first-mile'). This poses a conundrum for corporations and governments alike as they commit to deforestation-free sourcing and turn to instruments like certification to increase supply chain transparency and sustainability. The Roundtable on Sustainable Palm Oil (RSPO) offers the most influential certification system in the sector, but whether it actually reduces deforestation is still unclear. This study used remote sensing and spatial analysis to assess the deforestation (2009–2019) caused by oil palm plantation expansion in Guatemala, a major palm oil source for international consumer markets. Our results reveal that plantations are responsible for 28% of deforestation in the region and that more than 60% of these plantations encroach on Key Biodiversity Areas. RSPO-certified plantations, comprising 63% of the total cultivated area assessed, did not produce a statistically significant reduction in deforestation. Using trade statistics, the study linked this deforestation to the palm oil supply chains of three transnational conglomerates – Pepsico, Mondelēz International, and Grupo Bimbo – all of whom rely on RSPO-certified supplies. Addressing this deforestation and supply chain sustainability challenge hinges on three measures: 1) reform of RSPO policies and practices; 2) robust corporate tracking of supply chains; and 3) strengthening forest governance in Guatemala. This study offers a replicable methodology for a wide-range of investigations that seek to understand the transnational linkages between environmental change (e.g. deforestation) and consumption.

1. Introduction

Tropical deforestation – which is primarily driven by commodity production – has major, potentially irreversible, global implications for biodiversity (Benton et al., 2021), ecosystem functioning (IPBES, 2019), soil health (Foley et al., 2005), hydrological cycles (Bala et al., 2007), carbon emissions (Smith et al., 2014), and livelihoods (Newton and Benzeev, 2018). Beef, palm oil, soy, and wood products alone account for 40% of tropical deforestation globally (Henders et al., 2015).

Palm oil is particularly pernicious given its near ubiquity. Cheap, versatile, and easy to grow, it is the world's most consumed vegetable oil and is found in roughly half of all packaged supermarket products – from bread and butter, to shampoo and toothpaste (WWF, 2022a). Since 2000, palm oil production has more than tripled (Ceres, 2022) and an additional 36 million hectares (ha) of land will be required by 2050 to meet projected demand (Meijaard et al., 2020).

Scholarship on the connection between palm oil and deforestation has primarily focused on Southeast Asia, especially Indonesia and Malaysia, where most production occurs (Pendrill et al., 2019). But the region's producers face shrinking land availability and increasing scrutiny, driving expansion in new production geographies. With the largest global forest reserves suitable for oil palm production, Latin America has emerged as the next frontier and is already the second largest producing region (Castellanos-Navarrete et al., 2021; Furumo and Aide, 2017). In the span of just one decade (2010–2020), palm oil production in Latin America has more than doubled (FAOSTAT, 2020).

Palm oil expansion has been especially rapid in Guatemala, which boasts the highest productivity per ha globally (Tropical Forest Alliance, 2019). By 2030, Guatemala is projected to become the world's third largest palm oil producer, after Indonesia and Malaysia (Tropical Forest

* Corresponding author.
E-mail addresses: calliv@umich.edu (C.P. VanderWilde), jpnewell@umich.edu (J.P. Newell), dgounar@umich.edu (D. Gounaridis), ben.goldstein@mcgill.ca (B.P. Goldstein).

https://doi.org/10.1016/j.jenvman.2023.118505
Received 1 May 2023; Received in revised form 16 June 2023; Accepted 23 June 2023
Available online 1 July 2023
0301-4797/© 2023 Elsevier Ltd. All rights reserved.

Alliance, 2019). With conversion of forestland to oil palm plantations well-underway, conservationists are especially concerned about incursion into the Maya Biosphere Reserve, the largest contiguous rainforest in Guatemala (Barnhart, 2020; Furumo and Aide, 2017; Hodgon et al., 2015; Kuepper et al., 2021).

Unrelenting deforestation in the tropics from palm oil and other commodities has prompted the European Union to craft regulations requiring supply chains to be deforestation-free (European Commission, 2022). National governments are following suit, including in the U.K and the U.S. (Forest Act of 2021, 2021; DEFRA, 2021). Climate change mitigation policies, in both public and private sectors, are also starting to require accounting for Scope 3 greenhouse gas emissions, including those associated with land use (Gensler, 2022).

Voluntary certification schemes have emerged as a primary mechanism for improving supply chain transparency and commodity production practices, including meeting deforestation-free targets (Drost et al., 2022; Garrett et al., 2019; Lambin et al., 2018; Milder et al., 2015; RSPO, 2022). The Roundtable on Sustainable Palm Oil (RSPO) is among the most prominent of these certification initiatives and it is the only global sustainability standard covering edible oils (Bennett, 2017; Cattau et al., 2016; Pacheco et al., 2020; Pattberg, 2007). Certified members conform to a set of "Principles and Criteria" that ostensibly address environmental and social impacts associated with production (RSPO, 2020). This includes the protection of High Conservation Value and High Carbon Stock forests (Gatti et al., 2019; RSPO, 2020). Yet, in many ways the RSPO's effectiveness for forest protection is still debated (Carlson et al., 2018; Cattau et al., 2016; Dauvergne, 2018; Gatti et al., 2019; Gatti and Velichevskaya, 2020; Heilmayr et al., 2020a; Lee et al., 2020; Meijaard et al., 2017; Morgans et al., 2018; Noojipady et al., 2017).

These policy efforts all seek to harness the power of consumer markets to shape production practices in distant geographies. Land change science scholars describe these linkages between geographies of production and consumption as teleconnections or telecoupled systems (Seto et al., 2012). But unweaving the complex, often opaque supply chain linkages between sites of production and consumption is a distinct challenge. Although scholars have mapped broad sectoral flows connecting land cover change in one region to consumption in another (Friis and Nielsen, 2017), we generally lack sufficient tools to track corporate-specific supply chains, whether for giant multinational food conglomerates or smaller commodity-specific companies (Escobar et al., 2020; Goldstein and Newell, 2019, 2020; Hansen et al., 2022). Yet, given the enormous power these actors wield in the global economy, changing their behavior is necessary for the sustainable transition of production-consumption systems (Goldstein and Newell, 2019). Targeting the actions of just a few corporate actors can have profound impact.

In light of this, this study tracks the palm oil sourced from forestland and other ecologically critical areas of Guatemala by three transnational conglomerates – PepsiCo, Mondelēz International (hereafter, "Mondelēz"), and Grupo Bimbo – that sell food products made from this palm oil in the U.S. PepsiCo and Mondelēz International are the world's largest snack food companies while Grupo Bimbo is the third most powerful food conglomerate in the U.S. (Euromonitor International, 2021, 2022). All three are members of the RSPO and rely on RSPO-certified palm oil for their products (Grupo Bimbo, 2022a; Mondelēz International, 2023; PepsiCo, 2022a). Through this case study we seek to answer the following questions.

1. Where is palm oil grown in Guatemala and to what degree is it contributing to deforestation and ecological encroachment?
2. From where in Guatemala are these conglomerates importing palm oil and what are their supply chain configurations, from forest to consumer market?
3. Is RSPO-certification effective in reducing risks related to deforestation and ecological encroachment in these supply chains?

To answer these questions, we combined remote sensing, machine learning, and spatial analysis in concert with a methodological approach known as Tracking Corporations Across Space and Time (TRACAST) (Goldstein and Newell, 2020). Our results indicate that over a decade (2009–2019), a significant proportion of palm oil expansion in Guatemala led to deforestation and ecological encroachment. Supply chain reconstruction reveals explicit linkages between PepsiCo, Mondelēz, and Grupo Bimbo, these plantations, and their impacts. We do not find evidence that RSPO-certification effectively protects against deforestation or ecological encroachment. This suggests that despite company policies for complete, or near complete, RSPO coverage of their palm oil supplies, certification, at least in the context of Guatemala, is not an effective mechanism for guaranteeing corporate zero-deforestation commitments or robustly protecting against other environmental sourcing risks.

We conclude with concrete suggestions for improving the RSPO, as well as recommendations for advancing legislation and supply chain traceability and transparency, especially by tackling the "first-mile" problem. This problem is not limited to palm oil. Opaque supply chain origins impede our ability to link transnational supply chains to environmental and social impacts across all sectors (VanderWilde et al., 2023). Although this study prioritizes environmental impacts, how palm expansion affects livelihoods and land rights is equally important, including those of Indigenous Peoples and communities.

The utility of this study extends beyond Guatemala, palm oil, or even commodity production. It presents a broadly replicable and systematic method to uncover connections between complex transnational supply chains and distant land use change. Excavating and mapping these teleconnections provides a springboard for future work on production-consumption linkages, environmental degradation, carbon emissions, justice and equity, and corporate greenwash and governance.

2. Materials and methods

This study used remote sensing and machine learning to quantify deforestation attributable to oil palm expansion in Guatemala over a decade (2009–2019) and to assess whether RSPO-certification reduced this deforestation. To identify palm oil supply chain production-consumption linkages for three food conglomerates (PepsiCo, Mondelez, and Group Bimbo), we used the TRACAST methodological framework (Goldstein and Newell, 2020).

2.1. Assessment of deforestation

Our analysis covered 54,000 km^2 across the *departamentos* responsible for 75% of Guatemala's palm oil production during the study period: Alta Verapaz, Izabal, and (the lower, palm oil-producing portion of) Petén (Fig. 1). In 2019, Petén accounted for 46.03% of national palm oil production; Izabal for, 16.59%; and Alta Verapaz for, 14.20% (GREPALMA, 2020). This scope captures significant sectoral growth and permits land use change analysis with high-resolution satellite imagery. These *departamentos* also include ecologically significant subtropical forests, protected areas (PAs), and key biodiversity areas (KBAs) that provide important habitat for endangered species (BirdLife International, 2020; Ecosphere, 2022; IUCN, 2022a; UNESCO, 2019).

2.1.1. Data pre-processing

For land change analysis we acquired 5-m resolution imagery from Planet (www.planet.com). Asset classes were downloaded as orthorectified, calibrated, and corrected 4-band (red, green, blue, and NIR) imagery products that we mosaicked into layers covering the entire study area for 2009 and 2019, respectively. To minimize phenological variation, we prioritized images from winter months, especially December and January, Guatemala's driest periods.

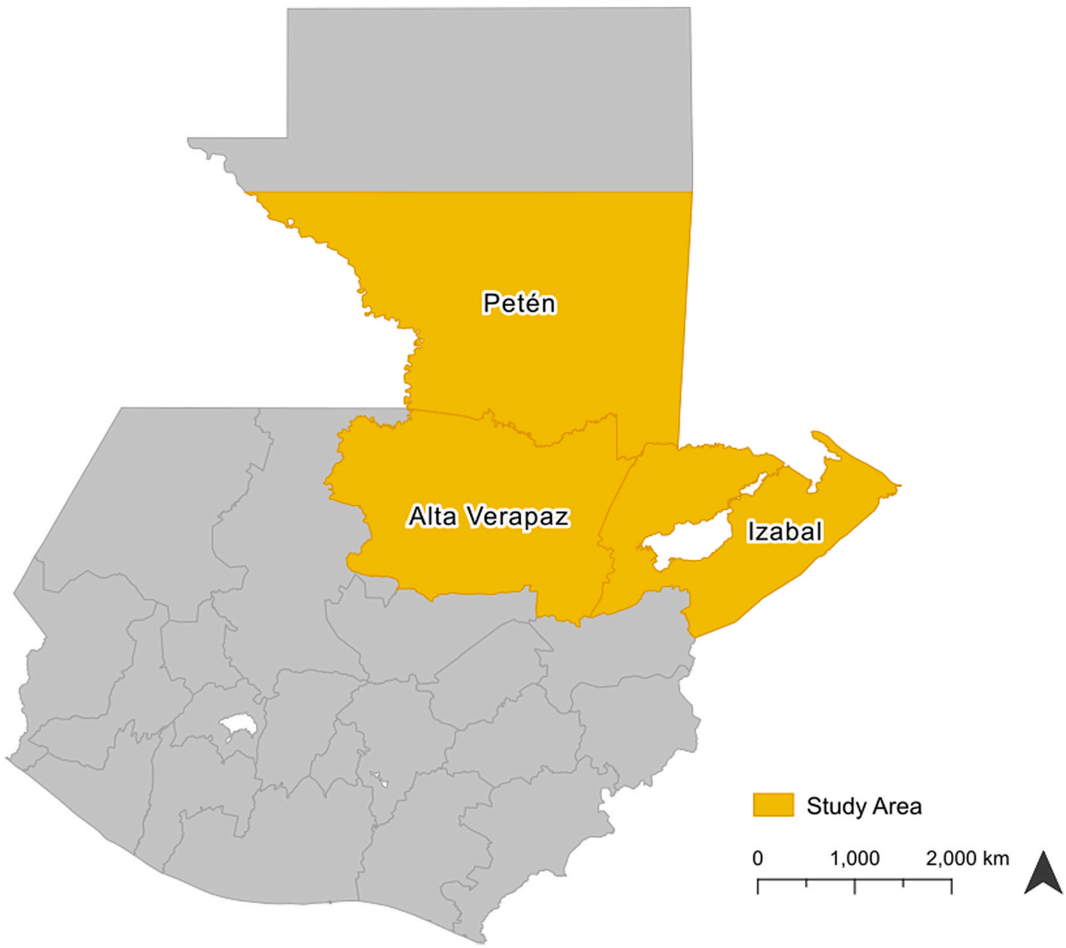

Fig. 1. The study area: Alta Verapaz, Izabal, and the lower half of Petén.

2.1.2. *Random Forests classification*

To map and quantify the deforestation (2009–2019) we utilized the Random Forest machine learning algorithm (Breiman, 2001) as it performs well in the face of heterogeneous classes (e.g., distinguishing between forests and monoculture plantations) and is computationally efficient compared to other methods (Belgiu and Drăguţ, 2016; Gislason et al., 2006).

To reduce complexity, we approached land use classification per *departamento* per year which resulted in six models. We trained these models on 11 initial land cover types, collecting thousands of samples per class via visual interpretation of the acquired imagery. To aid in interpretation, we consulted historical high-resolution (1 m) Google Earth imagery (nominal years 2009–2019) as well as historical land cover maps from the Guatemala Ministry of Agriculture, Livestock, and Food (*Ministerio de Agricultura, Ganadería y Alimentación*). The number of samples collected per class depended on class size and heterogeneity. Since similar spectral signatures present a challenge when working with heterogeneous classes like mature palm oil and forest, we avoided sampling along class boundaries (Gounaridis et al., 2016). To increase model performance and class representativeness, we also incorporated auxiliary vegetation and textural indices as predictors (Table S1) (Xu et al., 2021).

We ran the models in R using the *randomForest, caret*, *sp*, and *raster* packages (Hijmans, 2017; Kuhn, 2019; Liaw and Wiener, 2001; Pebesma et al., 2012; Team, 2000). To improve model output, we identified and removed outliers from the training samples before running the Random Forest models. For each run, we randomly selected 5 candidate variables at each split (mtry = 5) and grew 500 classification trees (ntree = 500).

2.1.3. *Classification results post-processing*

We post-processed results (by *departamento* and year), aggregating the initial land use classes into three categories: (1) palm plantation; (2) forest; and, (3) other. For post-processing, we replaced the values of individual isolated pixels with the mode of their neighborhood pixels (Gounaridis et al., 2014). Finally, we reclassified clearly misidentified patches of land by consulting plantation data from the RSPO (RSPO, 2021). To assess model accuracy, we took randomly distributed validation samples and manually identified land use class using Google Earth imagery. We then assessed producer, user, and overall accuracy of predictions per class and year (Table S2).

For each *departamento*, we estimated deforestation rates by cross-classifying and cross-tabulating the land use class of individual pixels. As a second layer of validation, we evaluated the accuracy of land use changes by visually cross-checking against Google Earth imagery (Table S3).

2.1.4. *Identifying encroachment of critical areas*

To determine the extent to which palm oil expansion has contributed to ecological encroachment, we cross-classified and cross-tabulated land change (2009–2019) within PAs and KBAs (BirdLife International, 2020; UNEP-WCMC, 2016). These datasets highlight ecological zones supporting a number of high conservation value species.

2.1.5. *Evaluating RSPO certification*

To add to the emerging literature on the effects of RSPO certification on deforestation and address gaps in the literature's geographic coverage, we used spatial regression modeling to determine whether RSPO-certification is associated with heightened deforestation and ecological encroachment, while accounting for other biophysical, climatic, economic, and geographic attributes of plantations. We combined our land change results with a suite of data from multiple sources (Table S4) including concession data from the RSPO (RSPO, 2021). Initially, we ran generalized linear models (GLM) to assess which factors contribute to deforestation and ecological encroachment. To fine-tune the models, we selected a set of predictors that balanced model complexity while minimizing the Akaike Information Criterion (AIC). We did not observe any multicollinearity effect among the independent variables (all variance inflation factor, values were less than 5) (Table 1).

Next, we calculated the Moran's I statistic which indicated significant spatial autocorrelation of fitted variables and model residuals (Dormann et al., 2007). To correct for spatial bias in our data we fitted a Spatial Lag model as indicated by the Lagrange multiplier test statistics (Anselin et al., 2009). For both the deforestation and ecological encroachment models, we calculated spatial contiguity using first-order Queen's adjacency methods via the *spatialreg* package in R (Bivand and Piras, 2015).

2.2. Supply chain reconstruction

To quantify corporate connections to palm oil deforestation, this study applied the TRACAST framework which scholars have previously used to locate and link corporate activities to environmental and social impacts for beef, avocados, rubber, and other commodities (Chamanara et al., 2021; Cho et al., 2021, 2022; Goldstein and Newell, 2020). Figs. 2 and 3 outline our TRACAST approach to linking distal U.S. demand for palm oil to deforestation in Guatemala.

2.2.1. Scope the study

We track Guatemalan exports of three palm oil products classified under the internationally standardized six-digit Harmonized Commodity Description and Coding System (HS) as: palm oil, crude (HS 1511.10); palm oil or fractions, simply refined (HS 1511.90); and palm kernel or babassu oil, crude (HS 1513.21). These products comprised ~98% of the country's palm oil exports between 2011 and 2019 (Chatham House, 2021) (Table S5). Mexico is the largest historical importer of palm oil from Guatemala (Chatham House, 2021; Fig. S1) and a major U.S. trade partner, so we scoped our study around Guatemala-Mexico-U.S. supply chain linkages. Once in Mexico, palm oil is used as an ingredient in many food products exported to U.S. consumer markets (Verite, 2014). We followed palm oil flows through Mexico-U.S. trade of food products classified as sweet biscuits (HS, 1905.31) and bread, pastry, cakes, biscuits and similar baked products, and puddings (HS, 1905.90). The U.S. is Mexico's largest historical export market for such goods (OEC, 2021). PepsiCo, Mondelēz, and Grupo Bimbo directed nearly 40% of these food product exports from Mexico in 2019.

2.2.2. Collect data and identify and verify linkages

To uncover linkages between actors and processes along the supply chain, we combined various data sources: transaction-level trade data (customs data), public mills lists, and public documents (e.g., NGO reports, GREPALMA[1] and RSPO publications, and newspaper articles) (Table S6).

2.2.3. Supply chain origins: The first-mile

Opaque supply chain origins often impede our ability to link transnational supply chains to environmental impacts. However, the quick processing requirements for fresh oil palm fruit bunches (Ramli et al., 2020) allowed us to infer the first-mile (e.g., plantation-mill connections) by geographically analyzing plantation sites, mill locations, and surrounding road infrastructure. We estimated the first-mile by: (1) creating an origin-destination matrix for all possible plantation-mill combinations using the QGIS Network Analysis Toolbox 3 (QNEAT3) plugin (Raffler, 2018); and (2) selecting the shortest path along the road network for each possible plantation-mill combination (Fig. S2; Table S7). When results indicated equal distances between a given plantation and multiple mills, we consulted ownership data or matched flows with the most immediately adjacent plantation. To verify model output, we compared results to RSPO data on linkages between certified plantations and mills.

Using annual production statistics from GREPALMA (2020) and data on plantation area, we then estimated the palm oil and palm kernel oil flows originating from each plantation in 2019. In later steps, we relied on first-mile linkages to assess supply chain connections to forest loss and ecological encroachment and to compare sourcing risks between RSPO-certified and non-certified plantations.

2.2.4. Palm oil supply chain flows

Using transaction-level customs data from Panjiva (2021) – which includes the names of shipping and consigning companies, their locations, and trade volume in mass and value – we identified 2,348 palm oil shipment records between Guatemala and Mexico in 2019. Based on these records, we established supply chain connections between Nodes 2 and 3 (Fig. 3) and estimated the mass of palm oil trade.

At manufacturing nodes, palm oil from various origins is intermixed and converted into ingredients destined for numerous end uses. These palm-oil derived ingredients take many different names which makes tracking specific flows beyond this point especially difficult (WWF, 2014). Moreover, their export from Mexico is relatively limited. However, by combining import statistics, domestic production data, and export figures, we estimated how Guatemalan palm oil continues to flow through Mexico as it becomes embodied in food products. While palm oil can be put towards many uses, 72% of the global palm oil market is used for food and beverage applications (Voora et al., 2019).

We determined linkages and flows between Mexico and the U.S. through 420 Panjiva shipment records of food products containing palm oil. We estimated the amount of palm oil of Guatemalan origin embodied in these food products using data on shipment weights; nutrient profiles of products (USDA, 2022); and statistics for Mexico's total imports, domestic production, and domestic consumption of palm oil (Fig. S3; Tables S10–18). Panjiva data covers 88% by mass of palm oil imports reported by Mexico (Chatham House, 2021; United Nations, 2021), which is suitable data coverage for tracking supply chains (Goldstein and Newell, 2020).

To establish linkages between mills and traders, and to geolocate mill nodes, we analyzed company documents, including annual reports and sourcing policies. While building linkages via text mining does not reveal mass flows of trade between companies, it does enable us to clarify how major conglomerates with a U.S. presence are linked to the production of Guatemalan palm oil. We also consulted corporate websites and annual reports to ascertain sourcing policies for palm oil, including any RSPO-based commitments.

3. Results

Our results indicate the supply chains of transnational conglomerates caused deforestation and ecological encroachment in Guatemala to support U.S. palm oil consumption. We estimated that oil palm plantations expanded 87,325 ha between 2009 and 2019 with 28% (24,609 ha) replacing forestland. A majority of oil palm plantations encroach on ecologically significant areas, replacing valuable habitat. We did not find evidence to suggest that RSPO-certification effectively protects against deforestation or ecological encroachment. Supply chain linkages reveal connections between palm oil production, certification, deforestation, and ecological encroachment. Despite RSPO membership and

[1] The Guild of Palmicultores of Guatemala, GREPALMA, for its Spanish acronym.

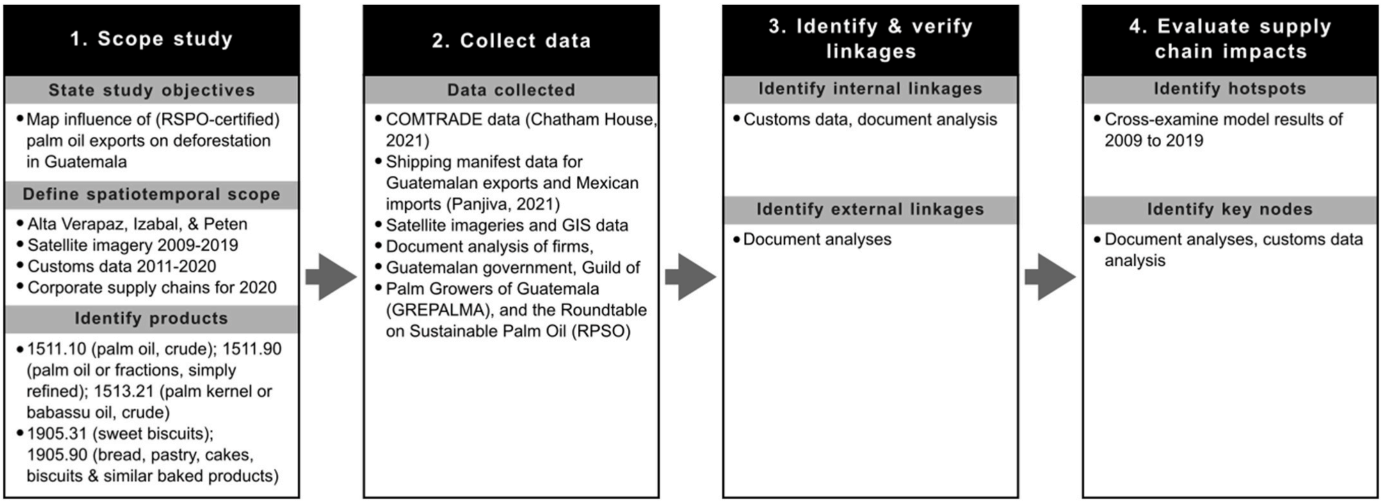

Fig. 2. TRACAST methodological framework used to map palm oil flows from forestland and other critical areas of Guatemala through the supply chains of three transnational conglomerates that sell food products in the U.S.

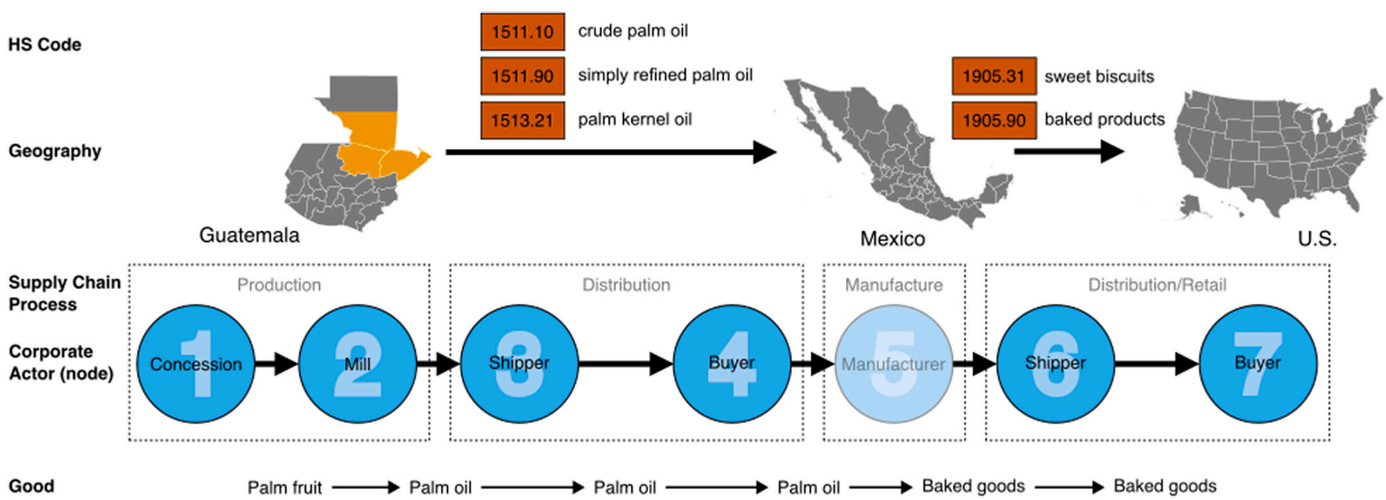

Fig. 3. Corporate actor (node) diagram of the supply chain carrying palm oil from Guatemala through Mexico and on to the U.S. Notes: The supply chain is segmented by geography, actor role (blue circles), and product Harmonized System (HS) codes (orange rectangles). Given that the domestic path palm oil takes from ingredient manufacturer to brand-name (food) product manufacturer is opaque, supply chain reconstruction does not include interactions between entities within Mexico.

procurement policies, Pepsico, Mondelēz, and Grupo Bimbo incur deforestation risks in their palm oil supply chains.

3.1. Mapping oil palm plantations and deforestation

Our remote sensing results indicate that palm oil production has increased 191% (2009: 45,753 ha; 2019: 133,078 ha) (Fig. 4). Findings for 2019 are comparable with GREPALMA statistics (131,712 ha of oil palm plantations) for the same year, providing additional validation (GREPALMA, 2020). Differences between our results and GREPALMA statistics are likely due to misclassification between forest and mature oil palm plantations. Such discrepancies aside, the Random Forest models still correctly identify forest loss due to oil palm expansion, achieving 90% and 94% overall accuracy for 2009 and 2019, respectively (Table S1). We find 371,835 ha of forest loss across the study area (Tables S8 and S9). Cross-classification results reveal 28% of palm oil expansion (24,609 ha) came at the expense of forestland (see Fig. 4).

Historically, agriculture has been a main deforestation driver, particularly due to expanding cropland and cattle pasture (Loening and Sautter, 2005). Extractive industries, including oil and timber, as well as expanding commercial agriculture, have also played a significant role (Cuéllar et al., 2011; Grandia, 2007). Illegal logging of rosewood (used to make musical instruments and high-end furniture) and infrastructure expansion for cocaine trafficking (Devine et al., 2020; Guo, 2019; McSweeney et al., 2014) are recent drivers of deforestation. Rates of oil palm-related deforestation vary by *departamento*: 14% in Petén, 3% in Izabal, and 2% in Alta Verapaz. Given that oil palm expansion is predicted to increase significantly in the coming years (Furumo and Aide, 2017; Tropical Forest Alliance, 2019), this deforestation pattern is likely to continue without changes to governance, both institutionally and across supply chains.

Our results show oil palm expansion is encroaching on and causing deforestation in 7 KBAs and 23 PAs (Fig. 4; Table S10). We find 67,476 ha (51%) of oil palm plantations by area overlap with KBAs and 41,059 ha (31%) with PAs. This expansion likely occurred as deforestation prior to 2009. Between 2009 and 2019, oil palm replaced 7,231 ha of forestland in KBAs (11%) and 5,202 (13%) ha of forestland in PAs. These findings suggest that land change induced by palm oil contributes to ecological encroachment, habitat destruction, and the endangerment of key species.

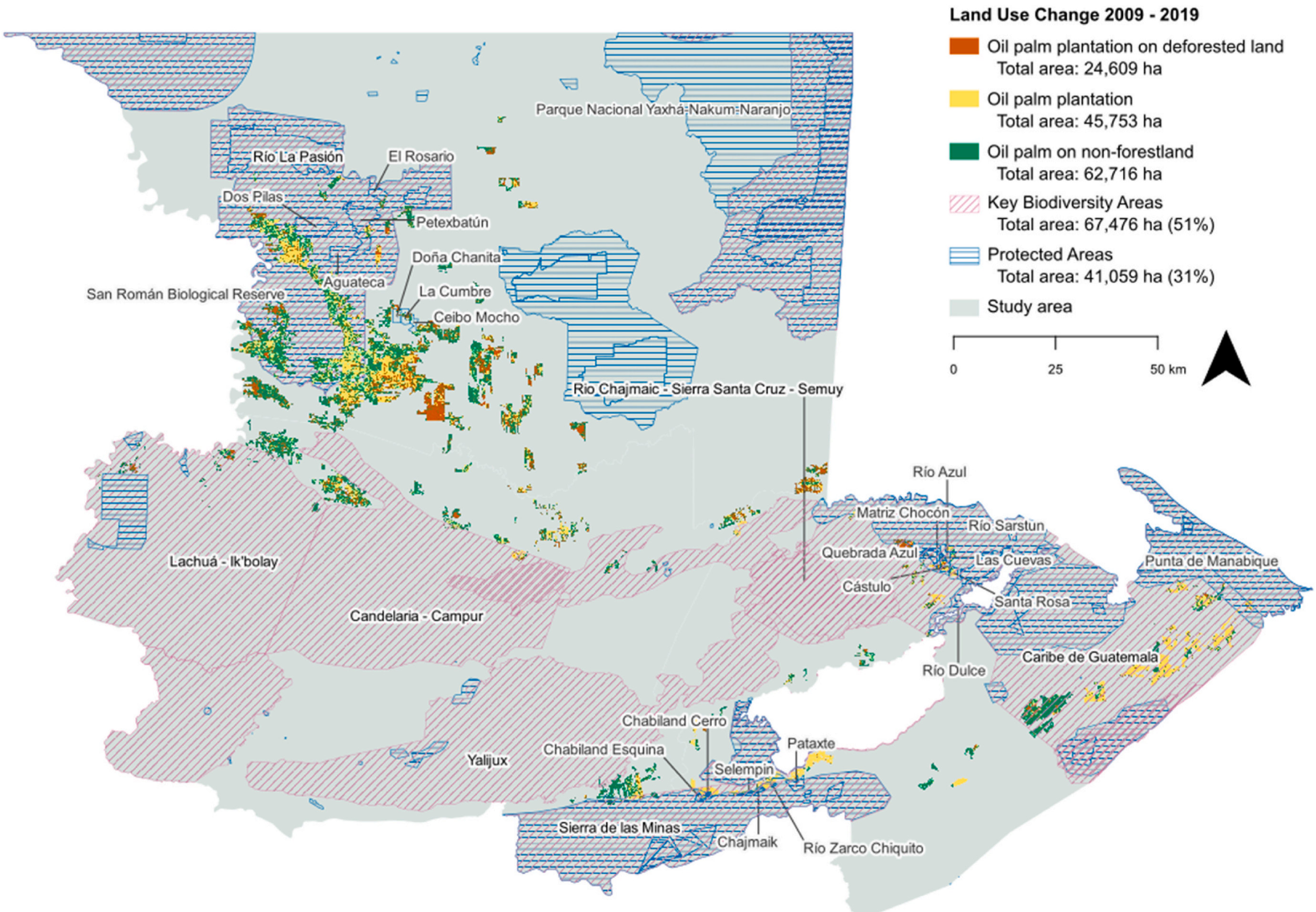

Fig. 4. Total oil palm driven deforestation across the study area (2009–2019) and oil palm plantation encroachment on ecologically significant areas (as of 2019). Orange indicates areas where oil palm has replaced forestland between 2009 and 2019. Yellow indicates areas that have remained oil palm, and green indicates areas where oil palm has replaced non-forestland. Fifty-one percent of plantations overlap with Key Biodiversity Areas and 31% with protected areas. Sources: BirdLife International (2020), UNEP-WCMC (2016).

Among the areas impacted, the KBAs with the largest palm extent include: Río La Pasión, Caribe de Guatemala, and the Sierra de las Minas Biosphere Reserve. The Río La Pasión is an especially rich area for endemic fish species making it an important area for conservation (Gobierno de la Republica de Guatemala, 2016). The area has already suffered significant environmental damage at the hands of the palm oil industry (Abbott, 2015, 2018). Oil palm expansion threatens the integrity of the broader San Román Biological Reserve which encompasses the Río La Pasión (Leitón, 2018) and provides critically needed habitats (de la Torre et al., 2017; IUCN, 2022a; Leitón, 2018). Oil palm encroachment on the Sierra de las Minas Biosphere threatens fauna like the quetzal (Guatemala's national bird; *Pharomachrus mocino*) (Krchnak, 2013; UNESCO, 2019). Called the "jewel" of Guatemala, this biosphere is an irreplaceable gene bank for tropical reforestation and agroforestry, and supports the livelihoods of over 400,000 people (Krchnak, 2013).

3.2. RSPO certification, deforestation, and ecological encroachment

In the study region, we identify 119 RSPO-certified plantations (32,772 ha) and 82 non-RSPO plantations (18,907 ha). Overall, we find 9% (3,038 ha) of forest loss (2009–2019) on RSPO-certified plantations, compared to 25% (4,764 ha) on non-certified plantations. We also find that 61% of RSPO-certified plantations (72) overlap with a KBA, and 27% (32) with a PA. Similarly, 63% of non-certified plantations (53) overlap with a KBA, and 22% (19) with a PA. Regression results (Table 1) suggest that RSPO-certification does not provide effective protection against deforestation or ecological encroachment, as certification was not a statistically significant predictor in either model. These results are robust when controlling for the influence of total plantation area; average annual precipitation and temperature; distance to palm oil mill, pastureland, and roads; population density; and slope. We did find that climatic and locational features, as well as plantation size, were significant predictors of oil palm-driven forest loss and ecological encroachment. These findings align with prior research on determinants of oil palm-driven forest loss in other contexts (Armenteras et al., 2013; Bax and Francesconi, 2018; Godar et al., 2012).

3.3. Supply chain reconstruction

Guatemalan palm oil is incorporated into manufactured food

Table 1
Results of the spatial Lag models used to determine whether RSPO-certification is associated with heightened deforestation and ecological encroachment (*** = $p <$ 0.001; ** = $p < 0.01$; * = $p < 0.05$).

Deforestation model						
	Estimate	Standard error	z-value	P-value	VIF	95% CI
(Intercept)	*−51.77*	*320.25*	*−0.16*	*0.87*		*−679.45–575.90*
RSPO-certification	*−6.56*	*13.16*	*−0.50*	*0.62*	*2.02*	*−32.34–19.23*
Total plantation area (ha)	*0.16****	*0.01*	*13.05*	*< 2.2e-16*	*1.42*	*0.14–0.19*
Ecological encroachment (ha)	*0.04*	*0.02*	*1.65*	*0.10*	*1.74*	*−0.01–0.08*
Average annual precipitation, mm	*0.05****	*0.01*	*4.03*	*0.00*	*3.38*	*0.03–0.08*
Average annual temperature, °C	*−3.96*	*11.64*	*−0.34*	*0.73*	*1.73*	*−26.78–18.86*
Distance to palm oil mill	*0.00*	*0.00*	*−1.09*	*0.28*	*1.24*	*−0.01–0.00*
Distance to pastureland	*−0.02**	*0.01*	*−1.95*	*0.05*	*1.70*	*−0.03–0.00*
Distance to road	*0.03*	*0.02*	*1.32*	*0.19*	*1.43*	*−0.02–0.08*
Population density, # of people per pixel	*−0.05*	*0.07*	*−0.65*	*0.52*	*1.38*	*−0.19–0.09*
Slope	*9.84*	*7.08*	*1.39*	*0.16*	*1.28*	*−4.03–23.71*
Ecological encroachment model						
	Estimate	*Standard error*	*z-value*	*P-value*	*VIF*	*95% CI*
(Intercept)	*3756.87****	*1004.64*	*3.74*	*0.00*		*1787.80–5725.93*
RSPO-certification	*−38.05*	*39.75*	*−0.96*	*0.34*	*2.01*	*−115.96–39.85*
Total plantation area (ha)	*0.20****	*0.05*	*4.00*	*0.00*	*2.48*	*0.10–0.29*
Deforestation (ha)	*0.29*	*0.21*	*1.38*	*0.17*	*2.46*	*−0.12–0.71*
Average annual precipitation, mm	*−119.10****	*36.06*	*−3.30*	*0.00*	*1.62*	*−189.78–−48.42*
Average annual temperature, °C	*−0.18****	*0.04*	*−4.04*	*0.00*	*3.35*	*−0.26–0.09*
Distance to palm oil mill	*−0.01*	*0.01*	*−1.15*	*0.25*	*1.24*	*−0.02–0.01*
Distance to pastureland	*0.01*	*0.02*	*0.49*	*0.63*	*1.77*	*−0.03–0.06*
Distance to road	*0.10*	*0.07*	*1.41*	*0.16*	*1.43*	*−0.04–0.25*
Population density, # of people per pixel	*0.25*	*0.21*	*1.19*	*0.23*	*1.37*	*−0.16–0.67*
Slope	*−1.81*	*21.46*	*−0.08*	*0.93*	*1.29*	*−43.87–40.24*

products through a series of supply chain transformations and actors (Fig. 3). Palm oil growers (Node 1), be they smallholders or plantation owners, deliver their harvested fresh fruit bunches to mills (Node 2), where both the oil palm fruit, a fleshy outer layer, and its seed, the kernel, are processed into crude palm oil and palm kernel oil respectively. In many cases, the Guatemalan trading and shipping companies (Node 3) are the same as the mill company or there are clear parent-subsidiary relationships. Mexican importers (Node 4), primarily

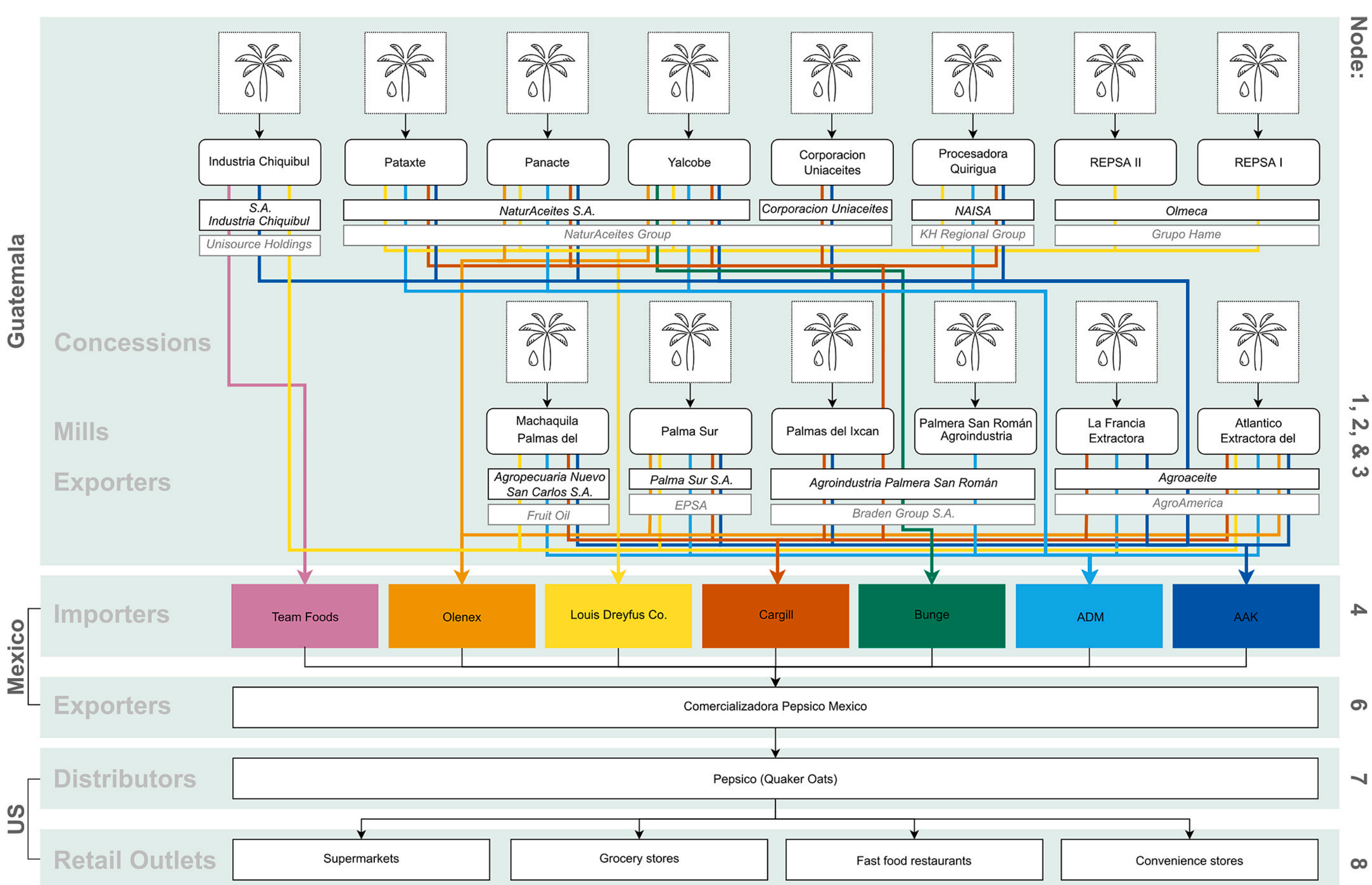

Fig. 5. PepsiCo palm oil supply chain from Guatemala, through Mexico, to the U.S.

companies in the edible oils manufacturing industry, produce a variety of palm oil derived ingredients that are used domestically in (food) product manufacturing (Node 5). Food products are then traded between Mexican shipping companies (Node 6) and U.S. distributors for major food brands (Node 7). Distributors stock a variety of retail outlets (Node 8) including groceries, supermarkets, convenience stores, and fast food restaurants.

We traced the supply chains for three leading multinational corporations – PepsiCo, Mondelēz, and Grupo Bimbo – establishing their respective supply chain linkages from oil palm plantations through to generalized U.S. retail outlets (Fig. 5 and Figs. S4–S5). Collectively, these three firms represent almost 40% of total exports (HS codes 1905.31, 1905.90) from Mexico to the U.S. in 2019.

PepsiCo has hundreds of brands. Its "Quaker Oats" arm consigns shipments from Mexico to the U.S. We estimate that these shipments embody 2,180 tons of palm oil sourced from 14 different mills (Fig. 5 and S2, Table 2). Of these mills, two are RSPO-certified and three are RSPO members. RSPO membership precedes certification: joining signals an intent to meet certification criteria over the coming years. As such, the supply bases of RSPO-member mills may only be partially certified.

Mondelēz manufactures and markets snack products under brands such as belVita, Chips Ahoy! Honey Maid, Nabisco, Oreo, and Ritz. We estimate that Mexico-U.S. shipments of these products include 600 tons of palm oil sourced from 7 different mills across the study region (Figs. S2 and S4, Table 2). Only two of these mills are associated with the RSPO, one is RSPO-certified and one is an RSPO member.

Grupo Bimbo produces a wide array of products, from breads and bagels to pastries and cookies. We estimate that shipments carry 4,330 tons of palm oil sourced from 14 different mills across the study area (Figs. S2 and S5, Table 2). Two of these mills are RSPO-certified and three are RSPO members.

By reconstructing the supply chains of these conglomerates to first-mile granularity, we reveal their connections to palm oil driven deforestation. Of the 24,609 ha of palm oil driven deforestation incurred across the study period, we connect more than 99% (24,518 ha) to the plantations supplying palm oil to PepsiCo's and Grupo Bimbo's palm oil mills and 72% (17,610 ha) to the subset of plantations supplying Mondelēz's palm oil mills (Table 2). The conglomerates' RSPO-certified mills collectively expanded on 3,584 ha of forestland.

4. Discussion

This work addresses gaps in the literature concerning corporate-specific supply chains, first-mile traceability, and the forest protection benefits offered by RSPO certification. Our findings reveal a number of interesting discussion points. First, the length and complexity of palm oil supply chains, like many other globalized product systems, make it difficult to establish causal links between land use change and consumption-based drivers. The first-mile problem in particular hinders the ability of corporations to identify their supply chain origins, which in turn hampers transparency and sustainability initiatives, including deforestation-free sourcing. Environmental certification does not effectively mitigate deforestation risk and firms cannot rely on (or be allowed to rely) on certification to achieve deforestation-free supply chains. Our results not only expand the existing literature on teleconnections and embodied deforestation, but also the literature on land-use related emission disclosures and corporate carbon performance, as we discuss below. In the following paragraphs, we discuss our findings and their implications as we suggest strategies that can help companies, and the sector writ large, eliminate risks in their palm oil supply chains.

4.1. *First-mile traceability*

The detailed end-to-end traceability established by this study adds precision to how and where deforestation dynamics and risks find their way into supply chains, allowing corporations – and their regulators – to connect statements of sustainability with evidence. This kind of granular traceability knowledge is essential for corporations to stay ahead of emerging deforestation-free regulations as well as indirect (Scope 3) carbon emissions assessments. It is likewise critical for external actors, such as regulators and watchdog organizations, to monitor compliance and progress towards related targets.

The end-to-end detail we present is not necessarily what companies themselves know. PepsiCo, Mondelēz and Grupo Bimbo have varyingly granular and stringent traceability systems for their palm oil supply chains (Grupo Bimbo, 2019a, 2022b; Mondelēz International, 2023; PepsiCo, 2022b). Mill-level traceability is relatively common. All three conglomerates, and many of their peers, make their mill lists readily available. However, Mondelēz is unique among the three

Table 2
Palm oil production and deforestation rates by mill.

Mill	RSPO status	Corporate connections	Oil palm plantations on forestland (ha)	Oil palm on non-forestland (ha)	Persistent oil palm plantations (ha)	% Deforested
Agroindustrial Palmera San Roman		Bimbo; PepsiCo	1,518	5,279	1,948	17%
Chiquibul		Bimbo; PepsiCo; Mondelēz	2,412	7,423	1,776	21%
Corporación Uniaceites		Bimbo; PepsiCo	719	1,464	463	27%
Extractora del Atlántico	Certified	Bimbo; PepsiCo; Mondelēz	1,203	3,316	10,924	8%
Extractora la Francia	Certified	Bimbo; PepsiCo	539	4,404	849	9%
Palma Sur		Bimbo; PepsiCo; Mondelēz	1,459	5,719	5,103	12%
Palmas del Ixcan		Bimbo; PepsiCo; Mondelēz	439	997	173	27%
Palmas del Machaquila		Bimbo; PepsiCo; Mondelēz	7,090	8,351	2,924	39%
Panacte		Bimbo; PepsiCo	496	4,505	2,533	7%
Pataxte		Bimbo; PepsiCo	166	458	3,065	4%
Procesadora Quirigua	Certified	Bimbo; PepsiCo; Mondelēz	1,842	6,780	3,847	15%
REPSA I	Member	Bimbo; PepsiCo	1,248	975	1,430	34%
REPSA II	Member	Bimbo; PepsiCo	2,220	7,354	7,075	13%
Yalcobe		Bimbo; PepsiCo; Mondelēz	3,167	5,571	3,551	26%
Total			**24,518**	**62,496**	**45,661**	

Note: RSPO membership precedes certification, merely signaling an intent to meet the criteria for certification over the coming years. REPSA I and REPSA II are listed in the RSPO membership database but only some of their plantations are certified.

conglomerates, and lead firms generally, in its prioritization of plantation-level traceability. Yet, its plantation data is confidential.

This trend means corporate traceability stops short of the plantation and obscures the first-mile, the supply chain stage connecting the site of raw material extraction to the initial transfer of custody of those natural resources, where most environmental impacts occur. Without traceability back to sites of production it is impossible for corporations to guarantee deforestation-free sourcing (Mol and Oosterveer, 2015). As a result, their unverified corporate sustainability claims can obfuscate reality.

With first-mile traceability, corporations can ground their claims to increase the credibility of their sustainable sourcing plans and mitigate external risk. Not only can first-mile traceability equip actors with information and tools to proactively address problems, but it can also work as a means of governance via threat of discovery and scandal (Brad et al., 2018). Linkages revealed through end-to-end traceability can indirectly implicate lead firms in the conditions surrounding material production. NGOs have historically targeted multinational corporations, including PepsiCo and Mondelēz, through name-and-shame campaigns designed to drive behavior change (Greenpeace International, 2016, 2018). In fact, some of the most notable campaign successes in the palm oil industry were motivated by companies targeted by NGO brand-activism (Richardson, 2015). Transparent and accessible first-mile traceability data has the potential to facilitate broader third-party monitoring and the ability to hold firms accountable.

Our first-mile traceability approach concretely demonstrates a method for obtaining more precise estimates of indirect (Scope 3) supply chain emissions assessments (Plambeck, 2012). The scale of greenhouse gas emissions driven by land use change makes tackling deforestation an increasing priority for companies working to decarbonize their supply chains. However, inconsistencies among existing methods for quantifying these emissions challenge corporate progress (Hansen et al., 2022), as does spatial aggregation of data (Escobar et al., 2020).

4.2. RSPO reform

The widespread adoption of, and confidence in, environmental certification to tackle commodity driven deforestation raises particular concern given our findings. Yet, these results echo other studies questioning the efficacy of voluntary corporate supply chain instruments (Dauvergne, 2018; Garrett et al., 2019; Pye, 2019) and they align with existing research on the (in)effectiveness of RSPO certification at reducing deforestation in other regions (Table 3).

Our findings indicate that despite their RSPO-membership and sourcing policies, PepsiCo, Mondelēz, and Grupo Bimbo are predominately sourcing from *non-certified* mills in Guatemala. Under the RSPO Credit system, they are able to claim fully sustainable palm oil while continuing to sell products containing uncertified oil. To account for the gaps in certified uptake they purchase additional sustainability certificates (Grupo Bimbo, 2019b; Mondelēz International, 2019; PepsiCo, 2019). Critics are skeptical of the indulgences the system permits, arguing it facilitates greenwash by absolving firms of supply chains monitoring responsibilities (Brad et al., 2018; Gallemore et al., 2022). Our findings support this claim, highlighting the importance of physically-certified palm oil models.

Troublingly, our findings also suggest that RSPO-certified mills and plantations still contribute to deforestation. Although RSPO criteria stipulates any new land clearing after 2005 cannot cause deforestation or damage primary, High Conservation Value, and High Carbon Stock forests (RSPO, 2020), this is happening in Guatemala. The RSPO standard is failing to sufficiently protect against deforestation or encroachment on ecologically important areas. As deforestation-free regulations proliferate, and as companies – and even countries – increasingly promise deforestation-free palm oil using the RSPO, acknowledging and addressing its shortcomings is particularly urgent (Donofrio et al., 2017; Furumo et al., 2020; Lambin et al., 2018; RSPO, 2016). Otherwise, corporate greenwashing may continue to threaten the integrity of the RSPO and its ability to effect meaningful change.

Table 3
Overview of the research on the (in)effectiveness of RSPO certification at reducing deforestation.

Country/ Region	Time period	Findings	Reference
Guatemala	2009–2019	No significant impact on forestloss or ecological encroachment	VanderWilde et al. (2023)
Indonesia	1984–2020	Strong relationship between deforestation and certified palm oil	Gatti and Velichevskaya (2020)
Indonesia	2009–2016	Reduced illegal deforestation but not deforestation rate	Heilmayr et al. (2020a)
Indonesia	2003–2014	Reduced deforestation and increased primary forest protection	Lee et al. (2020)
Indonesia, Malaysia, Papua New Guinea	2001–2016	Extensive forest loss prior to RSPO certification of plantations; Similar, if not higher, rates on certified plantations	Gatti et al. (2019)
Indonesia	2001–2015	Reduced but did not stop deforestation; Certified plantations had little remaining forest.	Carlson et al. (2018)
Indonesia	1999–2015	No significant difference in fire outbreaks on certified vs. non-certified plantations	Morgans et al. (2018)
Indonesia and Malaysia	2002–2014	Reduced, but did not stop, forest loss or fire activity; Plantations had little remaining forest	Noojipady et al. (2017)
Indonesia	2012–2015	Reduced fires only in areas with low likelihood of fires	Cattau et al. (2016)

Reports indicate that violations of the RSPO are systemic (EIA, 2015, 2019) providing little reassurance of its integrity. Others have suggested improving monitoring, verification, and enforcement with an expanded traceability system and improved audit structure to verify origins (Bishop and Carlson, 2022; EIA, 2019; Kusumaningtyas, 2017). Although growers are required to submit spatial data on their concessions, we found gaps which indicates a need for further oversight. This could fall on the RSPO Assurance Committee who could then utilize the dataset to remotely monitor land clearing and new plantings (EIA, 2019). Based on the results of their study in Indonesia, Carlson et al. (2018) also recommend the RSPO incentivize forest protection by creating price premiums linked to forest conservation. We recommend such incentives be extended to protect critical ecosystems broadly.

Although an important governing body for the palm oil sector, the RSPO is no silver bullet. Sustainable palm oil production also requires organized efforts and collaborations beyond the RSPO (Ruysschaert, 2016; Ruysschaert and Salles, 2018). Other action-oriented groups like the Palm Oil Innovation Group (POIG) and national or regional sustainable palm oil alliances can facilitate collective advocacy for sustainable palm oil (WWF, 2022b).

4.3. Deforestation policies

Promising legislation emerging in consumer countries aims to ensure that imported commodities, including palm oil, do not cause deforestation in producer countries (DEFRA, 2021; European Commission, 2022; FOREST Act of, 2021, 2021). PepsiCo, Mondelēz, and Grupo Bimbo distribute products across the United Kingdom and EU which subjects them to both the UK Environment Act and the EU Deforestation Law. Whether these companies maintain distinct supply chains to separate material flows and production based on final product destination is unclear. However, our results indicate that existing sources are problematic and non-compliant with regulations. Sourcing risks will continue to grow as other countries, including the U.S., enact deforestation legislation.

Scholars caution these policies may not be enough to protect forests and may harm smallholder livelihoods (Grabs et al., 2023; Zhunusova et al., 2022). For example, EU regulation benchmarks deforestation risk at the country-level which excludes regional variation and exacerbates the potential for deforestation leakage to other countries (Villoria et al., 2022). To improve this legislation, Grabs et al. (2023) suggest sub-national risk ratings for sourcing regions, common international standards, and financial incentives for first-movers. Smallholders may not have the knowledge or resources to meet new requirements, suggesting a need for policy measures that incentivize capacity building (Grabs et al., 2023; Zhunusova et al., 2022).

Many non-forested, but nonetheless critical ecosystems, are equally threatened by commodity expansion, as we have seen in the case of Guatemala. However, deforestation-centric legislation stands to leave these systems unprotected (Li et al., 2022; TNC, 2022). The IUCN (2022b) therefore calls for expanding legislation to protect all ecosystems threatened by commodity trade.

Although Guatemala's constitution includes provisos for preserving the environment and natural resources, legislation conflicts with these aspirations (Briz et al., 2021). For example, the Forestry Law allows for deforestation (Art. 46) and incentivizes the establishment of monoculture plantations (Art. 80) (Ley Forestal, 2013). Incentives for sustainable intensification (i.e., intensively managing plantations to enhance productivity on existing areas) (Monzon et al., 2021; Sharma et al., 2019), and planting on degraded land (Gingold et al., 2012) could make land clearing less attractive. The success of the Amazon Soy Moratorium indicates the potential for enacting a moratoria on the purchase of palm oil from deforested lands elsewhere (Heilmayr et al., 2020b; Lambin et al., 2018; Rausch, 2021).

Protecting the rights of local communities to manage and restore forests can help improve forest conservation and climate change mitigation while promoting environmental justice and strengthening local incomes, livelihoods and food sovereignty (Erbaugh et al., 2020; Palm Oil Detectives, 2021; Tenure Facility, 2021). However, in Guatemala and many other producer countries, long-standing tenure issues impede local peoples' ability to secure such benefits (Brent et al., 2018; Tramel, 2019; Zhunusova et al., 2022).

4.5. Future research opportunities

Oil palm plantations established prior to 2009 likely occupy previously forested land but data availability limited the temporal scope of this study. With better data, future work may be able to assess earlier historical land use changes. We structured the models in this study to identify forest-to-oil palm land use change dynamics, but it would also be of interest to understand other deforestation drivers in detail. In addition, it is critical to continuously monitor land use change impacts associated with commodity production. Our study provides a snapshot that ends in 2019, but the story continues to evolve.

While this study focused on teleconnections that embody the environmental risks of palm oil production, social risks are also pressing. This suggests an opportunity for an important future application of the presented methods: to identify corporate linkages to social impacts of production. For example, across the study area, aggressive expansion

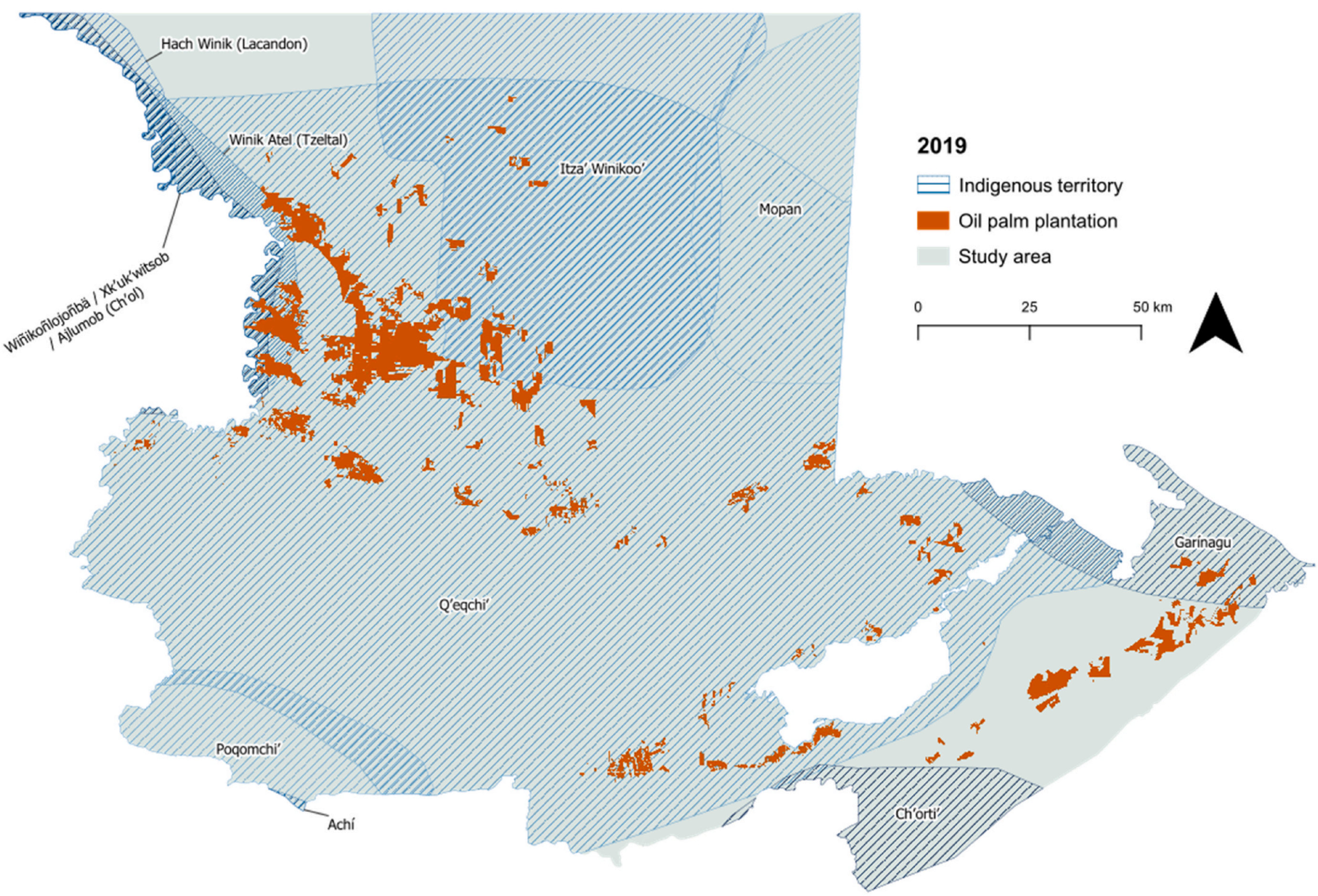

Fig. 6. Oil palm on Indigenous land across the study area. Source: Native Land (2022). Note: Boundaries indicate traditional territories and do not represent definitive or legal boundaries of any Indigenous nations.

has led to serious implications for the livelihoods and food security of indigenous populations, particularly the Mayan-Q'eqchi (Hervas, 2021). The land area now occupied by oil palm plantations covers the area equivalent to land once used by more than 60,000 subsistence farmers (Milton, 2018). Dozens of rural communities have been subsumed by oil palm plantations and others have disappeared entirely (Pietilainen and Otero, 2019). Dispossessed of the land they rely on for food, water, materials, shelter, and medicine – for life – already vulnerable populations experience further deteriorated food security, health, freedom of choice, and social ties (Alonso-Fradejas, 2012; Mingorría et al., 2014; Pietilainen and Otero, 2019). For Guatemala's Indigenous peoples, oil palm expansion represents the latest manifestation of longstanding historical processes of land-control grabbing (Pietilainen and Otero, 2019). These patterns of accumulation only perpetuate deeply inequitable land distribution in the country.

Further clarification of the land rights of Indigenous peoples is critically needed as oil palm, and other export-oriented crops, encroach on historically Indigenous areas (Fig. 6). Future research could focus on clarifying these land rights, identifying supply chain ties to dispossession, and documenting land conversion to oil palm – and other export-oriented crops. While best available data indicates the location of traditional territories, it does not necessarily reflect the views of local nations, definitive or legal boundaries, or current population distributions (Native Land, 2022). In the absence of concrete maps and adequate legal protections to delineate and protect their territories, communities remain vulnerable to systematic dispossession. Ancestral claims to land are disregarded for the benefit of large private landowners, ranchers and companies Mingorría et al., 2014. Community and national-level data layers on lands managed, owned, and held under customary tenure should be generated in partnership with Indigenous peoples and communities.

5. Conclusion

Palm oil has attracted significant attention for its ties to widespread forest and biodiversity loss across Southeast Asia. However, the literature has paid minimal attention to newer spaces of production and issues of corporate supply chain traceability. Understanding corporate-specific supply chains, from their origins, is critical for creating targeted interventions to address teleconnections to environmental and social impacts – and for empowering companies themselves with the knowledge to act. In this paper, we therefore sought to reveal how the plight of "sustainable" palm oil production is playing out in an emerging frontier. Our analysis suggests a tale foretold, with forests and other ecologically critical landscapes replaced by large-scale monoculture plantations. Across the study area, 28% of plantation expansion caused deforestation (2009–2019) and over 60% are in Key Biodiversity Areas, while 25% are in protected areas. We revealed corporate linkages to plantations and found that their RSPO-dependent sustainable palm oil commitments do not effectively protect corporations against environmental risks, as certification is not effectively curbing deforestation or ecological encroachment. As it stands, the environmental certification makes unjustified claims of "sustainability" and fails to serve as a reliable tool for fulfilling emerging zero-deforestation requirements. The strategies we have identified can help companies, and the sector writ large, eliminate such environmental risks in their supply chains.

Credit author statement

Conceptualization: Calli P. VanderWilde; Joshua P. Newell; Dimitrios Gounaridis; Benjamin P. Goldstein. Methodology: Calli P. VanderWilde; Joshua P. Newell; Dimitrios Gounaridis; Benjamin P. Goldstein. Software: Calli P. VanderWilde; Dimitrios Gounaridis. Validation: Calli P. VanderWilde; Dimitrios Gounaridis. Formal analysis: Calli P. VanderWilde; Dimitrios Gounaridis. Investigation: Calli P. VanderWilde. Resources: Calli P. VanderWilde. Data Curation: Calli P. VanderWilde; Dimitrios Gounaridis. Writing - Original Draft: Calli P. VanderWilde; Joshua P. Newell; Dimitrios Gounaridis; Benjamin P. Goldstein. Writing - Review & Editing: Calli P. VanderWilde; Joshua P. Newell; Dimitrios Gounaridis; Benjamin P. Goldstein. Visualization: Calli P. VanderWilde. Supervision: Joshua P. Newell; Dimitrios Gounaridis; Benjamin P. Goldstein.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118505.

References

Abbott, J., 2015. palm oil industry tied to ecocide in Guatemalan river. July 7 Upside Down World. https://upsidedownworld.org/archives/guatemala/palm-oil-industry-tied-to-ecocide-in-guatemalan-river/.

Abbott, J., 2018. A victory against ecocide in Guatemala: activist pressure forces nestlé to drop destructive palm oil producer. March 7 Toward Freedom. https://towardfreedom.org/story/archives/environment/a-victory-against-ecocide-in-guatemala-activist-pressure-forces-nestle-to-drop-destructive-palm-oil-producer/.

Alonso-Fradejas, A., 2012. Land control-grabbing in Guatemala: the political economy of contemporary agrarian change. Can. J. Dev. Stud./Rev. Can. Études Dev. 33 (4), 509–528. https://doi.org/10.1080/02255189.2012.743455.

Anselin, L., Syabri, I., Kho, Y., 2009. GeoDa: an introduction to spatial data analysis. In: Handbook of Applied Spatial Analysis: Software Tools, Methods and Applications. Springer, pp. 73–89.

Armenteras, D., Cabrera, E., Rodríguez, N., Retana, J., 2013. National and regional determinants of tropical deforestation in Colombia. Regional Environmental Change 13 (6), 1181–1193. https://doi.org/10.1007/s10113-013-0433-7.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C., Mirin, A., 2007. Combined climate and carbon-cycle effects of large-scale deforestation. In: Proceedings of the National Academy of Sciences, pp. 6550–6555. https://doi.org/10.1073/pnas.0608998104, 104(16).

Barnhart, E., 2020. Palm oil plantations threaten the rainforests and people of Guatemala. July 8 Maya Biosphere Watch. https://mayabiospherewatch.com/palm-oil-plantations-threaten-the-rainforests-and-people-of-guatemala/.

Bax, V., Francesconi, W., 2018. Environmental predictors of forest change: An analysis of natural predisposition to deforestation in the tropical Andes region, Peru. Applied Geography 91, 99–110. https://doi.org/10.1016/j.apgeog.2018.01.002.

Belgiu, M., Drăguţ, L., 2016. Random forest in remote sensing: a review of applications and future directions. ISPRS J. Photogrammetry Remote Sens. 114, 24–31. https://doi.org/10.1016/j.isprsjprs.2016.01.011.

Bennett, E.A., 2017. Who governs socially-oriented voluntary sustainability standards? Not the producers of certified products. World Dev. 91, 53–69.

Benton, T.G., Bieg, C., Harwatt, H., Pudasaini, R., Wellesley, L., 2021. Food system impacts on biodiversity loss. Three levers for food system transformation in support of nature. Chatham House, London.

BirdLife International, 2020. Key biodiversity areas GIS data. https://www.keybiodiversityareas.org/kba-data/request.

Bishop, K.J., Carlson, K.M., 2022. The role of third-party audits in ensuring producer compliance with the Roundtable on Sustainable Palm Oil (RSPO) certification system. Environ. Res. Lett. 17 (9) https://doi.org/10.1088/1748-9326/ac8b96, 094038.

Bivand, R., Piras, G., 2015. Comparing implementations of estimation methods for spatial econometrics. J. Stat. Software 63, 1–36.

Brad, A., Delemare, A., Hurley, N., Lenikus, V., Mulrenan, R., Nemes, N., Trunk, U., Urbancic, N., 2018. The false promise of certification. Changing Markets Foundation. http://changingmarkets.org/wp-content/uploads/2018/05/False-promise_full-report-ENG.pdf.

Breiman, L., 2001. Random forests. Mach. Learn. 45 (1), 5–32. https://doi.org/10.1023/A:1010933404324.

Brent, Z.W., Alonso-Fradejas, A., Colque, G., Sauer, S., 2018. The 'tenure guidelines' as a tool for democratising land and resource control in Latin America. Third World Q. 39 (7), 1367–1385. https://doi.org/10.1080/01436597.2017.1399058.

Briz, R., Volpicella, K., Gramajo, J.P., 2021. Environmental Law and practice in Guatemala: overview. Practical Law. http://uk.practicallaw.thomsonreuters.com/w-013-2794?contextData=(sc.Default)&transitionType=Default&firstPage=true.

Carlson, K.M., Heilmayr, R., Gibbs, H.K., Noojipady, P., Burns, D.N., Morton, D.C., Walker, N.F., Paoli, G.D., Kremen, C., 2018. Effect of oil palm sustainability certification on deforestation and fire in Indonesia. In: Proceedings of the national academy of sciences of the united states of america. NATL ACAD SCIENCES, pp. 121–126. https://doi.org/10.1073/pnas.1704728114, 115, Issue 1.

Castellanos-Navarrete, A., de Castro, F., Pacheco, P., 2021. The impact of oil palm on rural livelihoods and tropical forest landscapes in Latin America. J. Rural Stud. 81, 294–304. https://doi.org/10.1016/j.jrurstud.2020.10.047.

Cattau, M.E., Marlier, M.E., DeFries, R., 2016. Effectiveness of Roundtable on Sustainable Palm Oil (RSPO) for reducing fires on oil palm concessions in Indonesia from 2012 to 2015. In: Environmental Research Letters. IOP Publishing Ltd. https://doi.org/10.1088/1748-9326/11/10/105007, 11, Issue 10.

Ceres, 2022. *Palm oil* (an investor brief on impacts that drive business risks). Ceres. https://engagethechain.org/sites/default/files/commodity/Ceres%20Brief%20-%20Palm%20Oil.pdf.

Chamanara, S., Goldstein, B., Newell, J.P., 2021. Where's the beef? Costco's meat supply chain and environmental justice in California. J. Clean. Prod. 278, 123744.

House, Chatham, 2021. *'Resourcetrade.earth.'* resource trade. https://resourcetrade.earth/.

Cho, K., Goldstein, B., Gounaridis, D., Newell, J.P., 2021. Where does your guacamole come from? Detecting deforestation associated with the export of avocados from Mexico to the United States. J. Environ. Manag. 278, 111482.

Cho, K., Goldstein, B., Gounaridis, D., Newell, J.P., 2022. Hidden risks of deforestation in global supply chains: a study of natural rubber flows from Sri Lanka to the United States. J. Clean. Prod. 349, 131275.

Cuéllar, N., Kandel, S., Davis, A., Díaz, O., Luna, F., Ortiz, X., 2011. Territorial dynamics in Central America: context and challenges for rural communities. Fundación PRISMA, San Salvador.

Dauvergne, P., 2018. The global politics of the business of "sustainable" palm oil. Global Environ. Polit. 18 (2), 34–52.

de la Torre, J.A., Núñez, J.M., Medellín, R.A., 2017. Habitat availability and connectivity for jaguars (Panthera onca) in the Southern Mayan Forest: conservation priorities for a fragmented landscape. Biol. Conserv. 206, 270–282. https://doi.org/10.1016/j.biocon.2016.11.034.

Devine, J.A., Currit, N., Reygadas, Y., Liller, L.I., Allen, G., 2020. Drug trafficking, cattle ranching and Land use and Land cover change in Guatemala's Maya Biosphere Reserve. Land Use Pol. 95, 104578 https://doi.org/10.1016/j.landusepol.2020.104578.

Donofrio, B., Rothrock, P., Leonard, J., 2017. Supply change: tracking corporate commitments to deforestation-free supply chains. (p. 32. Forest Trends. https://www.forest-trends.org/wp-content/uploads/2017/03/2017SupplyChange_FINAL.pdf.

Dormann, C.F., McPherson, J.M., Araújo, M.B., Bivand, R., Bolliger, J., Carl, G., Davies, R.G., Hirzel, A., Jetz, W., Kissling, W.D., 2007. Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. Ecography 609–628.

Drost, S., Rijk, G., Piotrowski, M., 2022. EU deforestation regulation: implications for the palm oil industry and its financers. Chain reaction research. https://chainreactionresearch.com/report/eu-deforestation-regulation-implications-for-the-palm-oil-industry-and-its-financers/.

Ecosphere, 2022. Forest conservation in the Guatemalan caribbean. https://ecosphere.plus/wp-content/uploads/2022/03/Ecosphere-Guatemala-Conservation-Coast.pdf.

Environmental Investigation Agency (EIA), 2015. Who watches the watchmen. https://eia-international.org/wp-content/uploads/EIA-Who-Watches-the-Watchmen-FINAL.pdf.

Environmental Investigation Agency (Eia), 2019. Who watches the watchmen 2. Environmental investigation agency (EIA). https://eia-international.org/wp-content/uploads/WWtW2-spreads.pdf.

Erbaugh, J.T., Pradhan, N., Adams, J., Oldekop, J.A., Agrawal, A., Brockington, D., Pritchard, R., Chhatre, A., 2020. Global forest restoration and the importance of prioritizing local communities. Nature Ecology & Evolution 4 (11). https://doi.org/10.1038/s41559-020-01282-2. Article 11.

Escobar, N., Tizado, E.J., zu Ermgassen, E.K.H.J., Löfgren, P., Börner, J., Godar, J., 2020. Spatially-explicit footprints of agricultural commodities: mapping carbon emissions embodied in Brazil's soy exports. Global Environ. Change 62, 102067. https://doi.org/10.1016/j.gloenvcha.2020.102067.

Euromonitor International, 2021. Bimbo bakeries USA inc in staple foods (USA). https://www-portal-euromonitor-com.proxy.lib.umich.edu/portal/Analysis/Tab.

Euromonitor International, 2022. Mondelez international inc in snacks (world). https://www-portal-euromonitor-com.proxy.lib.umich.edu/portal/Analysis/Tab.

European Commission, 2022. Law to fight global deforestation and forest degradation [Text]. December 6 European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7444.

FAOSTAT, 2020. Food and agriculture organization of the united nations. FAOSTAT database [Rome] : FAO, c1997-.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309 (5734), 570–574. https://doi.org/10.1126/science.1111772.

Forest Act of, 2021. 2021, S.2950. Congress 117. http://www.congress.gov/.

Friis, C., Nielsen, J.Ø., 2017. On the system. Boundary choices, implications, and solutions in telecoupling land use change research. Sustainability; Basel 9 (6), 974 org.proxy.lib.umich.edu/10.3390/su9060974.

Furumo, P.R., Aide, T.M., 2017. Characterizing commercial oil palm expansion in Latin America: land use change and trade. Environ. Res. Lett. 12 (2), 24008 https://doi.org/10.1088/1748-9326/aa5892.

Furumo, P.R., Rueda, X., Rodríguez, J.S., Parés Ramos, I.K., 2020. Field evidence for positive certification outcomes on oil palm smallholder management practices in Colombia. J. Clean. Prod. 245, 118891. https://doi.org/10.1016/j.jclepro.2019.118891.

Gallemore, C., Delabre, I., Jespersen, K., Liu, T., 2022. To see and be seen: technological change and power in deforestation driving global value chains. Global Networks, n/a (n/a). https://doi.org/10.1111/glob.12383.

Garrett, R.D., Levy, S., Carlson, K.M., Gardner, T.A., Godar, J., Clapp, J., Dauvergne, P., Heilmayr, R., le Polain de Waroux, Y., Ayre, B., Barr, R., Døvre, B., Gibbs, H.K., Hall, S., Lake, S., Milder, J.C., Rausch, L.L., Rivero, R., Rueda, X., Villoria, N., 2019. Criteria for effective zero-deforestation commitments. Global Environ. Change 54, 135–147. https://doi.org/10.1016/j.gloenvcha.2018.11.003.

Gatti, R.C., Velichevskaya, A., 2020. Certified "sustainable" palm oil took the place of endangered Bornean and Sumatran large mammals habitat and tropical forests in the last 30 years. Sci. Total Environ. 742, 140712.

Gatti, R.C., Liang, J., Velichevskaya, A., Zhou, M., 2019. Sustainable palm oil may not be so sustainable. In: SCIENCE OF THE TOTAL ENVIRONMENT. ELSEVIER, pp. 48–51. https://doi.org/10.1016/j.scitotenv.2018.10.222 vol. 652.

Gensler, G., 2022. Statement on proposed mandatory climate risk disclosures. US securities and exchange commission. https://www.sec.gov/news/statement/gensler-climate-disclosure-20220321.

Gingold, B., Stolle, F., Douard, P., Rosenbarger, A., Muliastra, Y.I.K.D., 2012. How to Identify Degraded Land for Sustainable Palm Oil in Indonesia.

Gislason, P.O., Benediktsson, J.A., Sveinsson, J.R., 2006. Random Forests for land cover classification. Pattern Recogn. Lett. 27 (4), 294–300. https://doi.org/10.1016/j.patrec.2005.08.011.

Gobierno de la Republica de Guatemala, 2016. Caso rio La pasion, peten, Guatemala [powerpoint]. https://www.iucn.org/sites/default/files/content/documents/2016/emegencia_rio_la_pasion_2016.pdf.

Godar, J., Tizado, E.J., Pokorny, B., 2012. Who is responsible for deforestation in the Amazon? A spatially explicit analysis along the Transamazon Highway in Brazil. Forest Ecology and Management 267, 58–73. https://doi.org/10.1016/j.foreco.2011.11.046.

Goldstein, B., Newell, J.P., 2019. Why academics should study the supply chains of individual corporations. J. Ind. Ecol. 23 (6), 1316–1327. https://doi.org/10.1111/jiec.12932.

Goldstein, B., Newell, J.P., 2020. How to track corporations across space and time. Ecol. Econ. 169, 106492 https://doi.org/10.1016/j.ecolecon.2019.106492.

Gounaridis, D., Zaimes, G.N., Koukoulas, S., 2014. Quantifying spatio-temporal patterns of forest fragmentation in Hymettus Mountain, Greece. Comput. Environ. Urban Syst. 46, 35–44. https://doi.org/10.1016/j.compenvurbsys.2014.04.003.

Gounaridis, D., Apostolou, A., Koukoulas, S., 2016. Land cover of Greece, 2010: a semi-automated classification using random forests. J. Maps 12 (5), 1055–1062. https://doi.org/10.1080/17445647.2015.1123656.

Grabs, J., Lyons-White, J., Garrett, R., 2023. Deforestation: proposed EU import ban may fail to protect tropical rainforests and farmers – here's how it should work. The Conversation. http://theconversation.com/deforestation-proposed-eu-import-ban-may-fail-to-protect-tropical-rainforests-and-farmers-heres-how-it-should-work-196968.

Grandia, L., 2007. Between bolivar and bureaucracy: the mesoamerican biological corridor. Conserv. Soc. 5 (4), 478–503.

Grupo Bimbo, 2019a. Política Global de Aceite de Palma Plan de Acción Año, vol. 4, p. 4.

Grupo Bimbo, 2019b. RSPO Annual Communication of Progress 2019: Corporativo Bimbo S.A. de C.V. RSPO. https://rspo.org/members/9111.

Grupo Bimbo, 2022a. Política Global de Aceite de Palma Plan de Acción Año 7 (2022), 3.

Grupo Bimbo, 2022b. Annual report 2021. https://informe-anual-grupobimbo.com/2021/en/baked-for-nature.

Greenpeace International, 2016. Cutting deforestation out of palm oil – company scorecard (p. 16. Greenpeace International. https://www.greenpeace.org/usa/research/cutting-deforestation-palm-oil-company-scorecard/.

Greenpeace International, 2018. Dying for a Cookie: how Mondelēz is feeding the climate and extinction crisis (p. 48. Greenpeace International. https://www.greenpeace.org/international/publication/19274/dying-cookie-mondelez-feeding-climate-extinction-crisis.

GREPALMA., 2020. Anuario Estadístico 2018-2019: agroindustria Sostenible de Aceite de Palma en Guatemala. https://www.grepalma.org/biblioteca-virtual/anuario-estadistico/.

Guo, E., 2019. The fight to protect the world's most trafficked wild commodity. August 16 Natl. Geogr. https://www.nationalgeographic.com/animals/article/guatemala-fight-against-rosewood-trafficking.

Hansen, A.D., Kuramochi, T., Wicke, B., 2022. The status of corporate greenhouse gas emissions reporting in the food sector: an evaluation of food and beverage manufacturers. J. Clean. Prod. 361, 132279 https://doi.org/10.1016/j.jclepro.2022.132279.

Heilmayr, R., Carlson, K.M., Benedict, J.J., 2020a. Deforestation spillovers from oil palm sustainability certification. Environ. Res. Lett. 15 (7), 75002 https://doi.org/10.1088/1748-9326/ab7f0c.

Heilmayr, R., Rausch, L.L., Munger, J., Gibbs, H.K., 2020b. Brazil's Amazon Soy Moratorium reduced deforestation. Nature Food 1 (12). https://doi.org/10.1038/s43016-020-00194-5. Article 12.

Henders, S., Persson, U.M., Kastner, T., 2015. Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities.

Environ. Res. Lett. 10 (12), 125012 https://doi.org/10.1088/1748-9326/10/12/125012.
Hervas, A., 2021. Mapping oil palm-related land use change in Guatemala, 2003–2019: implications for food security. Land Use Pol. 109, 105657 https://doi.org/10.1016/j.landusepol.2021.105657.
Hijmans, R.J., 2017. Introduction to the 'raster' Package (Version 2.6-7), vol. 27.
Hodgon, B.D., Hughell, D., Ramos, V.H., McNab, R.B., 2015. Tendencias en la deforestación de la Reserva de Biosfera Maya, Guatemala 2000-2013. Guatemala, USAID.
IPBES., 2019. Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. Zenodo. https://doi.org/10.5281/zenodo.6417333.
IUCN., 2022a. The IUCN red list of threatened species. https://www.iucnredlist.org. Version 2022, -1.
IUCN., 2022b. EU adopts Regulation for deforestation free products: effective complementary measures key for conservation. December 6 IUCN. https://www.iucn.org/news/202212/eu-adopts-regulation-deforestation-free-products-effective-complementary-measures-key.
Krchnak, K., 2013. Guatemala water fund: partnering with the private sector for biodive. https://www.slideshare.net/iwlpcu/guatemala-water-fund-partnering-with-the-private-sector-for-biodiversity-conservation-in-the-sierra-de-las-minas-biosphere-reserve-smbr-through-a-payment-for-environmental-services-pes-mechanism.
Kuepper, B., Drost, S., Piotrowski, M., 2021. Latin American Palm Oil Linked to Social Risks, Local Deforestation. Chain Reaction Research, Washington, DC, USA.
Kuhn, M., 2019. The caret Package. https://topepo.github.io/caret/.
Kusumaningtyas, R., 2017. External concerns on the RSPO and ISPO certification schemes. Profundo. https://www.foeeurope.org/sites/default/files/euus_trade_deal/2018/report_profundo_rspo_ispo_external_concerns_feb2018.pdf.
Lambin, E.F., Gibbs, H.K., Heilmayr, R., Carlson, K.M., Fleck, L.C., Garrett, R.D., Waroux, Y., le, P., de McDermott, C.L., McLaughlin, D., Newton, P., Nolte, C., Pacheco, P., Rausch, L.L., Streck, C., Thorlakson, T., Walker, N.F., 2018. The role of supply-chain initiatives in reducing deforestation. Nature Climate Change; London 8 (2), 109–116. https://doi.org/10.1038/s41558-017-0061-1.
Lee, J.S.H., Miteva, D.A., Carlson, K.M., Heilmayr, R., Saif, O., 2020. Does oil palm certification create trade-offs between environment and development in Indonesia. Environ. Res. Lett. 15 (12), 124064 https://doi.org/10.1088/1748-9326/abc279.
Leitón, M.D.Z., 2018. High Conservation Value Assessment Summary (HCV): reforestadora de Palmas de el Peten S.A. (REPSA) (p. 67. Bioterra. https://repsa.com.gt/wp-content/uploads/2021/02/PUBLIC-SUMMARY-HCV-REPSA-convertido.pdf.
Ley Forestal, 2013. Pub. L. No. Decreto No 101/96, 35. https://faolex.fao.org/docs/pdf/gua10056.pdf.
Li, B., Schneider, T., Stolle, F., Veldhoven, S. van, 2022. How a new EU regulation can reduce deforestation globally. https://www.wri.org/insights/eu-deforestation-regulation.
Liaw, A., Wiener, M., 2001. Classification and regression by RandomForest. Forest@ 23.
Loening, L.-J., Sautter, H., 2005. What drives biodiversity loss in the land of trees? A review of the economic and historical parameters causing deforestation in Guatemala. In: Markussen, M., Buse, R., Garrelts, H., Máñez Costa, M.A., Menzel, S., Marggraf, R. (Eds.), Valuation and Conservation of Biodiversity: Interdisciplinary Perspectives on the Convention on Biological Diversity. Springer, pp. 391–418. https://doi.org/10.1007/3-540-27138-4_19.
McSweeney, K., Nielsen, E.A., Taylor, M.J., Wrathall, D.J., Pearson, Z., Wang, O., Plumb, S.T., 2014. Drug policy as conservation policy: narco-deforestation. Science 343 (6170), 489–490. https://doi.org/10.1126/science.1244082.
Meijaard, E., Morgans, C., Husnayaen, N.K.A., Ancrenaz, M., 2017. An impact analysis of RSPO certification on Borneo forest cover and orangutan populations. Pongo Alliance.
Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A., Lee, J.S.H., Santika, T., Juffe-Bignoli, D., Struebig, M.J., Wich, S.A., Ancrenaz, M., Koh, L.P., Zamira, N., Abrams, J.F., Prins, H.H.T., Sendashonga, C.N., Murdiyarso, D., Furumo, P.R., Sheil, D., 2020. The environmental impacts of palm oil in context. Nature Plants 6 (12). https://doi.org/10.1038/s41477-020-00813-w. Article 12.
Milder, J.C., Arbuthnot, M., Blackman, A., Brooks, S.E., Giovannucci, D., Gross, L., Kennedy, E.T., Komives, K., Lambin, E.F., Lee, A., Meyer, D., Newton, P., Phalan, B., Schroth, G., Semroc, B., Rikxoort, H.V., Zrust, M., 2015. An agenda for assessing and improving conservation impacts of sustainability standards in tropical agriculture. Conserv. Biol. 29 (2), 309–320. https://doi.org/10.1111/cobi.12411.
Milton, L., 2018. The curse of palm oil in Guatemala. December 14 Roads & Kingdoms. https://roadsandkingdoms.com/2018/fighting-for-land-in-guatemala/.
Mingorría, S., Gamboa, G., Martín-López, B., Corbera, E., 2014. The oil palm boom: socio-economic implications for Q'eqchi'households in the Polochic valley, Guatemala. Environ. Dev. Sustain. 16 (4), 841–871.
Mol, A.P., Oosterveer, P., 2015. Certification of markets, markets of certificates: tracing sustainability in global agro-food value chains. Sustainability 7 (9), 12258–12278.
Mondelēz International, 2019. RSPO annual communication of progress 2019: mondelēz international. RSPO. https://document.rspo.org/2021/Mondelez_International_Inc_ACOP2021.pdf.
Mondelēz International, 2023. Mondelēz international, inc. Palm Oil. Retrieved March 27. https://www.mondelezinternational.com/Snacking-Made-Right/ESG-Topics/Palm-Oil.
Monzon, J.P., Slingerland, M.A., Rahutomo, S., Agus, F., Oberthür, T., Andrade, J.F., Couëdel, A., Edreira, Rattalino, J, I., Hekman, W., van den Beuken, R., Hidayat, F., Pradiko, I., Purwantomo, D.K.G., Donough, C.R., Sugianto, H., Lim, Y.L., Farrell, T., Grassini, P., 2021. Fostering a climate-smart intensification for oil palm. Nat. Sustain. 4 (7) https://doi.org/10.1038/s41893-021-00700-y. Article 7.
Morgans, C.L., Meijaard, E., Santika, T., Law, E., Budiharta, S., Ancrenaz, M., Wilson, K. A., 2018. Evaluating the effectiveness of palm oil certification in delivering multiple sustainability objectives. In: Environmental Research Letters. IOP PUBLISHING LTD. https://doi.org/10.1088/1748-9326/aac6f4, 13, Issue 6.
Native Land, 2022. Welcome. Native Land. https://native-land.ca/.
Newton, P., Benzeev, R., 2018. The role of zero-deforestation commitments in protecting and enhancing rural livelihoods. Curr. Opin. Environ. Sustain. 32, 126–133. https://doi.org/10.1016/j.cosust.2018.05.023.
Noojipady, P., Morton, D.C., Schroeder, W., Carlson, K.M., Huang, C., Gibbs, H.K., Burns, D., Walker, N.F., Prince, S.D., 2017. Managing fire risk during drought: the influence of certification and El Nino on fire-driven forest conversion for oil palm in Southeast Asia. In: Earth System Dynamics. Copernicus Gesellschaft Mbh, pp. 749–771. https://doi.org/10.5194/esd-8-749-2017, 8, Issue 3.
OEC., 2021. Oec - the observatory of economic complexity. Mexico (MEX) Exports, Imports, and Trade Partners. https://oec.world/en/profile/country/mex/?yearSelector1=exportGrowthYear25.
Pacheco, P., Schoneveld, G., Dermawan, A., Komarudin, H., Djama, M., 2020. Governing sustainable palm oil supply: disconnects, complementarities, and antagonisms between state regulations and private standards. Regulation & Governance 14 (3), 568–598. https://doi.org/10.1111/rego.12220.
Palm Oil Detectives, 2021. The pro-palm oil lobby getting caught lying: illegal land grabbing. July 24 Palm Oil Detectives. https://palmoildetectives.com/2021/07/24/the-pro-palm-oil-lobby-getting-caught-lying-illegal-land-grabbing/.
Panjiva, 2021. Panjiva HS Code 1511.10, 1511.90, and 1513.21 Shipments Results 2011-2020. panjiva.Com/.
Pattberg, P.H., 2007. Private institutions and global governance. The new politics of environmental sustainability. Edward Elgar.
Pebesma, E., Bivand, R., Pebesma, M.E., RcolorBrewer, S., Collate, A.A.A., 2012. Package 'sp.' the Comprehensive R Archive Network.
Pendrill, F., Persson, U.M., Godar, J., Kastner, T., 2019. Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. Environ. Res. Lett. 14 (5), 55003 https://doi.org/10.1088/1748-9326/ab0d41.
PepsiCo, 2019. RSPO annual communication of progress 2019: PepsiCo. RSPO. https://rspo.org/members/300.
PepsiCo, 2022a. ESG topics A to Z: deforestation. PepsicoUpgrade. https://pepsico.com/our-impact/esg-topics-a-z/deforestation.
PepsiCo, 2022b. Palm oil. PepsicoUpgrade. https://pepsico.com/our-impact/esg-topics-a-z/palm-oil.
Pietilainen, E.P., Otero, G., 2019. Power and dispossession in the neoliberal food regime: oil palm expansion in Guatemala. J. Peasant Stud. 46 (6), 1142–1166. https://doi.org/10.1080/03066150.2018.1499093.
Plambeck, E.L., 2012. Reducing greenhouse gas emissions through operations and supply chain management. Energy Econ. 34, S64–S74. https://doi.org/10.1016/j.eneco.2012.08.031.
Pye, O., 2019. Commodifying sustainability: development, nature and politics in the palm oil industry. World Dev. 121, 218–228. https://doi.org/10.1016/j.worlddev.2018.02.014.
Raffler, C., 2018. QNEAT3-QGIS network analysis Toolbox 3. QNEAT3. Https://Root676.Github.Io/Index.Html. (Accessed 27 December 2021).
Ramli, U.S., Tahir, N.I., Rozali, N.L., Othman, A., Muhammad, N.H., Muhammad, S.A., Tarmizi, A.H.A., Hashim, N., Sambanthamurthi, R., Singh, R., Manaf, M.A.A., Parveez, G.K.A., 2020. Sustainable palm oil—the role of screening and advanced analytical techniques for geographical traceability and authenticity verification. *Molecules, 25*(12), article 12. https://doi.org/10.3390/molecules25122927.
Rausch, L.L., 2021. Brazil's Amazon Soy Moratorium Deforestation Fronts, p. 2 (WWF).
Richardson, B., 2015. Making a market for sustainability: the commodification of certified palm oil. New Polit. Econ. 20 (4), 545–568. https://doi.org/10.1080/13563467.2014.923829.
Roundtable on Sustainable Palm Oil (Rspo), 2016. National commitments. https://www.rspo.org/about/national-commitments.
Roundtable on Sustainable Palm Oil (Rspo), 2020. RSPO principles and criteria for production of sustainable palm oil 2018. RSPO. https://rspo.org/wp-content/uploads/rspo-principles-criteria-for-production-of-sustainable-palm-oil-2018revised-01-february-2020-with-updated-supply-chain-requirements-for-mills.pdf.
Roundtable on Sustainable Palm Oil (Rspo), 2021. RSPO member concessions. Global forest watch. www.globalforestwatch.org.
Roundtable on Sustainable Palm Oil (Rspo), 2022. Press release: rspo's response to the political agreement on the deforestation regulation. December 8 Roundtable on Sustainable Palm Oil (RSPO). https://rspo.org/press-release-rspos-response-to-the-political-agreement-on-the-deforestation-regulation/.
Ruysschaert, D., 2016. The impact of global palm oil certification on transnational governance, human livelihoods and biodiversity conservation. Policy Matters 45.
Ruysschaert, D., Salles, D., 2018. The strategies and effectiveness of conservation NGOs in the global voluntary standards: the case of the roundtable on sustainable palm oil. In: Larsen, P.B., Brockington, D. (Eds.), Anthropology of Conservation ngos: Rethinking the Boundaries. Palgrave, pp. 121–149. https://doi.org/10.1007/978-3-319-60579-1_5.
Seto, K.C., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D.K., Olah, B., Simon, D., 2012. Urban land teleconnections and sustainability. Proc. Natl. Acad. Sci. U. S. A 109 (20), 7687–7692. https://doi.org/10.1073/pnas.1117622109.
Sharma, S.K., Baral, H., Laumonier, Y., Okarda, B., Komarudin, H., Purnomo, H., Pacheco, P., 2019. Ecosystem services under future oil palm expansion scenarios in West Kalimantan, Indonesia. Ecosyst. Serv. 39, 100978. https://doi.org/10.1016/j.ecoser.2019.100978.

Smith, P., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Roble do Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Chapter 11—Agriculture, Forestry and Other Land Use (AFOLU). Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter11.pdf.

Team, R.C., 2000. R language definition. Vienna, Austria: R Foundation for Statistical Computing 3 (1).

Tenure Facility, 2021. Indigenous forest management pivotal in the fight against biodiversity loss and climate change. Tenure Facility. https://thetenurefacility.org/article/indigenous-forest-management-pivotal-in-the-fight-against-biodiversity-loss-and-climate-change/.

TNC paper on EU deforestation legislation: the critical role of incentives and engagement with producer countries in ensuring success. https://www.nature.org/content/dam/tnc/nature/en/documents/FINAL_TNC_Paper_EU_Deforestation_Legislation.pdf, 2022.

Tramel, S.F., 2019. The tenure guidelines in policy and practice: democratizing land control in Guatemala. Land 8 (11). https://doi.org/10.3390/land8110168. Article 11.

Tropical Forest Alliance, 2019. A "Commodity-First"Approach to Identifying Landscapes for Private Sector Engagement.

UNEP-WCMC., 2016. The world database on protected areas (WDPA). https://umich.maps.arcgis.com/apps/mapviewer/index.html?layers=ae78aeb913a343d69e950b53e29076f7.

UNESCO., 2019. Sierra de las Minas Biosphere Reserve, Guatemala. June 25. UNESCO. https://en.unesco.org/biosphere/lac/sierra-de-las-minas.

United Nations, 2021. UN Comtrade. United Nations. https://comtrade.un.org/data/.

U.S. Department of Agriculture (USDA), 2022. FoodData Central [Database]. https://fdc.nal.usda.gov/fdc-app.html#/food-search.

VanderWilde, C.P., Goldstein, B., Newell, J.P., 2023. Out of sight, out of mind: defining and addressing the first-mile traceability problem in supply chains. Manuscript in Preparation.

Verite, 2014. Labor and human rights risk analysis of the Guatemalan palm oil sector. Verite. http://www.verite.org/sites/default/files/images/RiskAnalysisGuatemalanPalmOilSector.pdf.

Villoria, N., Garrett, R., Gollnow, F., Carlson, K., 2022. Leakage does not fully offset soy supply-chain efforts to reduce deforestation in Brazil. Nat. Commun. 13 (1) https://doi.org/10.1038/s41467-022-33213-z. Article 1.

Voora, V., Larrea, C., Bermudez, S., Baliño, S., 2019. Global market report: palm oil. International Institute for Sustainable Development Manitoba: Canada.

WWF., 2014. Which everyday products contain palm oil? World wildlife fund. https://www.worldwildlife.org/pages/which-everyday-products-contain-palm-oil.

WWF., 2022a. 8 things to know about palm oil. WWF. https://www.wwf.org.uk/updates/8-things-know-about-palm-oil.

WWF., 2022b. WWF palm oil buyers scorecard. Palm oil scorecard. https://palmoilscorecard.panda.org/.

Xu, K., Qian, J., Hu, Z., Duan, Z., Chen, C., Liu, J., Sun, J., Wei, S., Xing, X., 2021. A new machine learning approach in detecting the oil palm plantations using remote sensing data. Rem. Sens. 13 (2) https://doi.org/10.3390/rs13020236. Article 2.

Zhunusova, E., Ahimbisibwe, V., Sen, L.T.H., Sadeghi, A., Toledo-Aceves, T., Kabwe, G., Günter, S., 2022. Potential impacts of the proposed EU regulation on deforestation-free supply chains on smallholders, indigenous peoples, and local communities in producer countries outside the EU. For. Pol. Econ. 143, 102817. https://doi.org/10.1016/j.forpol.2022.102817.

Department for Environment, Food & Rural Affairs (DEFRA), Natural England, The Rt Hon George Eustice MP, Forestry Commission, & Environment Agency. (2021, November 10). *World-leading Environment Act becomes law*. GOV.UK. https://www.gov.uk/government/news/world-leading-environment-act-becomes-law.