Bausano *et al.*
Agricultural and Food Economics (2023) 11:35
https://doi.org/10.1186/s40100-023-00268-5

Agricultural and Food Economics

RESEARCH

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Food, biofuels or cosmetics? Land-use, deforestation and CO_2 emissions embodied in the palm oil consumption of four European countries: a biophysical accounting approach

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Abstract

Around 75% of tropical deforestation in the XXI century has been driven by the expansion of agriculture and forest plantations. Since 1990s, palm oil has been standing for a critical global traded product in terms of embodied deforestation. The European Union (EU) is one of the major players in terms of embodied deforestation linked to palm oil consumption. By adopting a biophysical accounting approach, the study: (1) investigated the palm oil imports between 2000 and 2020 by four EU countries (Germany, France, Italy, and Spain) from Indonesia, Malaysia, and Papua New Guinea, (2) estimated the share of imports driven by the demand from the food, oleochemicals, and energy sectors, and (3) quantified land, deforestation, and CO_2 emissions associated with Land-Use Change (LUC) embodied in trade. Different trade profiles have emerged among the four importing countries. Italy and Spain showed a major direct trade link with producing countries, while France and Germany have significant connections with non-producing countries (i.e. intermediate trade partners). Overall, our results show that, following different trends, leading consumption sectors have shifted from the food towards the energy sector. Consequently, the growing demand for palm oil as a feedstock for biofuel production has determined increased environmental impacts in South-East Asia. Since 2000, the total embodied land footprint has increased four-fold, while, over the period considered, according to our second and the third attribution approaches (i.e. historical and rapid-conversion), between 5–78 m^2 of deforestation and 28–445 kg CO_2 emissions associated with LUC activities have been incorporated in the per-capita consumption of palm oil and its co-products in the leading European economies. Moreover, according to the first attribution approach (i.e. concession-level) and the allocation by sector, we concluded that, between 2004 and 2016, the German food sector is the one that embodied the larger deforestation footprint, followed by the Italian and Spanish energy sectors.

Keywords: Tropical deforestation, Palm oil, Global trade, Land footprint, Embodied deforestation, RSPO, Biophysical accounting models, Land use impact assessment

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Introduction

Deforestation trends, hotspots, and drivers

Forests, mainly tropical rainforests, are recognized as major contributors to enhance terrestrial biodiversity, fight against climate change, and deliver a range of ecosystem services (FAO and UNEP 2020). Global Land-Use Change (LUC) processes, in particular deforestation, have been acknowledged as one of the main drivers of climate change, loss of terrestrial biodiversity, and natural ecosystems fragmentation (Foley et al. 2005; IPCC 2014; Persson et al. 2014; Diaz et al., 2019). While forests represent nearly 45% of the terrestrial carbon pools (Waring et al. 2020), tropical deforestation drives around 25% of total net global carbon emissions (Skutsch et al. 2007).

According to FAO, (2020), on average about 5 Mha of global forests have been lost annually since the beginning of the XXI century. Around 75% of tropical deforestation has been driven by the expansion of agriculture and forest plantations to produce wood and non-wood products (Persson et al. 2014; Brack et al. 2016; Curtis et al. 2018; WWF 2021). Between 2011 and 2015, agriculture expansion directly drove the conversion of 6.4–8.8 Mha of tropical forests (Pendrill et al. 2022a). More than 90% of this annual forest loss took place within specific tropical "deforestation hotspots" (Curtis et al. 2018; Pendrill et al. 2019a, 2022a; WWF 2021). On average, about half of the global annual tropical deforestation directly linked to the agriculture and forestry sectors is located within only two countries: Brazil (33%) and Indonesia (14–19%) (Pendrill et al. 2019a). Moreover, between 1990 and 2009, deforestation driven by the expansion of permanent croplands and pastures became the second and fourth drivers[1] of global carbon emissions related to LUC activities, respectively (Houghton 2012).

According to several studies (Lawson 2014; Persson et al. 2014; Niu et al. 2020), a rising share of these commodity-driven deforestation activities is associated with large-scale production of farm operators exporting globally. By outsourcing their internal demand for raw materials, developed countries are displacing local land use to producing countries (Weinzettel et al. 2013; Liu et al. 2021). As a result, the liberalization of international trade has been identified as one of the fundamental indirect drivers of the contemporary exploitation and degradation of environmental resources at the global scale (Barbier 2000; Pendrill et al., 2019a, 2022a). According to Wiedmann et al. (2018), up to 70% of global socio-environmental impacts stem from the international demand for goods and services. In addition, DeFries et al. (2010) demonstrated a positive and significant correlation between a country's agricultural trade (i.e., export volume) and domestic forest loss. As a result, environmental impacts are "embodied" into global trade flows. For instance, international trade has been associated, as an indirect driver, with 64% and 30–40% of the land and deforestation footprints directly linked to the global production of agricultural and animal products. (Cuypers et al. 2013; Pendrill et al., 2019a; IPCC 2020; Liu et al. 2021). Furthermore, according to Pendrill et al. (2019b) 29–39% of the total carbon emissions associated with LUC in tropical countries were driven by the international demand of Forest Risk Commodities (FRCs).

[1] The first is shifting cultivation (i.e. crops growth and forest recovery alternate on the same land unit), while the third is draining and burning of peatlands (Houghton 2012).

Globally, among the main FRCs, beef, soybeans, and palm oil production was the cause of about 60% of tropical deforestation during the XXI century. This proportion rises to 75% by including wood and paper (Pendrill et al., 2019a). Consequently, beef and vegetable oil production have concurrently driven more than half of the Green-House Gases (GHGs) emissions falling within the "Agriculture, Forestry and Other Land Use" (AFOLU) sector (IPCC 2020).

Since 2014, palm oil is, among the main FRCs, the only one increasing its impact in terms of annual embodied deforestation (ha/yr) (Wood E&IS GmbH, 2021).

Palm oil production, consumption, and global trade patterns

Since 1960, on average, about 85% of total palm oil production has taken place within the Asian tropical belt, especially in Malaysia, Indonesia, and Thailand, 8–9%, in Africa,[2] 5–6%, in Central and South America,[3] and the remaining 1–2% in Oceania, almost exclusively within Papua New Guinea (PNG) (Faostat, 2021). Between 1970 and 2018, Malaysia and Indonesia increased their production by + 97%. In 2019, of the 28 Mha of oil palms farmed worldwide, 52% and 18% were respectively located in Indonesia and Malaysia (Fig. 2). These two countries currently produce nearly 90% of palm oil consumed globally (EC, 2018).

Since 1961, on average, about 25–40% of the palm oil produced in Indonesia, Malaysia and PNG has served the domestic markets, while 58% served the Asian continent, with India (27%) and China (24%) being the leading importers (Pacheco et al. 2017; Voora et al. 2020). In 2016, India, China and Indonesia accounted for 40% of the total palm oil consumption in the food sector (Voora et al. 2020). All in all, since 1960, over 70% of the global palm oil imports have been made up by India, China, and the EU 27. Between 2000 and 2021, the latter increased palm oil imports from Indonesia and Malaysia by 60%, while, together, the two Asian countries by 66% (Faostat, 2023).

Deforestation and carbon emissions driven by the palm oil sector in South-East Asia

It is estimated that, on average, though with significant sub-regional differences, in South-East Asia at least 45% of actual oil palm plantations have replaced forest areas present in 1989 (Vijay et al. 2016; EC, 2018). Moreover, according to Gaveau et al. (2016), between 1973 and 2015, on average, 20.5% of the new palm oil plantations in Indonesia and Malaysia have started production activities within the first 5 years from the start of logging activities (rapid conversion). According to Austin et al. (2019), between 2000 and 2016, in Indonesia, palm oil production has been, on average, the main direct deforestation driver (23%).

Deforestation activities driven by the expansion of the palm oil sector in Indonesia, Malaysia, and PNG have strongly determined a reduction of carbon stocks and the emission of large quantities of CO_2 into the atmosphere (Agus et al. 2013a, 2013b; Guillaume et al. 2018; Carlson et al. 2012; Harris et al. 2013; Hooijer et al. 2010). Globally, up to 80% of the total carbon emissions linked to global palm oil production have been associated with LUC activities (Efeca 2022). According to Greenpeace International (2013), about

[2] Especially in Nigeria, Ivory Coast, and the Democratic Republic of Congo (Faostat 2021).

[3] Especially in Colombia, Ecuador and Brazil (Faostat 2021).

85% of GHG emissions in Indonesia are linked to LUC processes, half of which are associated with the conversion/degradation of peat swamp forests (i.e. peatlands), which represent 20% of the LU converted into palm oil plantations between 1995 and 2015 (Austin et al. 2017). The loss of peatlands[4](-32% in Indonesia and Malaysia between 2007 and 2015) together with fires (25% of palm oil-driven deforestation in the period 2002–2014) (Noojipady et al. 2017) have determined the highest share of carbon emissions in South-East Asia (Harris et al. 2013; Miettinen et al. 2016; EC 2018). According to Hooijer et al. (2010), the forested tropical peatlands drainage in South-East Asia represented up to 3.1% of the global fossil-fuel CO_2 emissions. Currently less than 40% of the native peatland forests in Malaysia, Indonesia and PNG still exist, with only 6 to 9% standing in a discrete state of conservation (Schrier-Uijl et al. 2013; Miettinen et al. 2016; EC 2018). According to Agus et al. (2013a), the annual net emissions caused by the loss of forest biomass, fires, and drainage of peatlands in Indonesia, Malaysia, and PNG rose from 92 $MtCO_2$/yr between 1990 and 2000 to 106 $MtCO_2$/yr between 2001 and 2005 and finally up to 184 $MtCO_2$/yr between 2006 and 2010. Harris et al. (2013) quantified another 264 $MtCO_2$/yr emissions for the period 2010–2020.

Personn et al. (2014) estimated a LUC carbon footprint of 7.5tCO_2 per ton of imported palm oil. Through a different method, Flynn et al. (2012) quantified 8tCO_2-eq, 6.1tCO_2-eq, and 6.3tCO_2-eq of LUC emissions embodied in the import of one ton of Indonesian, Malaysian, and Papua New Guinea palm oil.

The role of the EU

Within this context, since 1990, the EU, being a larger importer and consumer of the palm oil traded globally, has become one of the largest importer of FRCs on a per-capita basis (Cuypers, 2013; Lawson 2015; Fuchs et al. 2020; Heflich 2020). Between 2005 and 2017, nine European countries[5]were responsible for 80% of the EU28's embodied deforestation, indirectly driving 3.5 Mha of deforestation—equivalent to 5m^2/per-capita—and 1.8 Mt of associated CO_2 emissions (WWF 2021).

The EU consumption of palm oil has grown from representing nearly 10% of the total EU embodied deforestation for the period 1990–2008 (Brack 2016)–0.9 Mha—(Cuypers et al. 2013) to 24% for the period 2005–2017, up to 42% in 2017 (WWF 2021). Due to this growth, between 1990 and 2017, palm oil ranked second (after soybeans) among crops in terms of embodied deforestation per unit of EU imported product (Cuypers et al. 2013; Pendrill et al., 2019a; WWF 2021).

The prominent position of the EU within the global trade of FRCs has recently led to the development of policies and tools specifically aimed at reshaping and halting the import trends of FRCs. A proposal for a regulation on deforestation-free products was published by the EC in November 2021, building upon the experiences of the EU Timber Regulation (EUTR) and the EU Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan. A mandatory due diligence for all operators placing FRCs on the

[4] After swamp forest logging, the drainage of Peatlands, through drainage canals and the subsequent lowering of water levels, determine the decomposition of waterlogged organic matter and thus the release into the atmosphere of organic carbon (Hamada et al. 2016).

[5] Belgium, Denmark, France, Germany, Italy, Poland, the Netherlands, Spain, and the United Kingdom.

EU market or exporting them outside the EU borders was included and refined in the regulation proposal (EC 2021; Mubareka et al. 2021).

End uses of palm oil

In terms of LU, palm oil, since 2006 the most produced vegetable oil in the world, currently accounts for nearly 40% of global vegetable oil consumption, while—due to higher yields—ranking only fourth within the vegetable oils sector[6] in terms of area harvested[7] (Meijaard et al. 2020; Faostat 2022). Besides higher yields, the growth of the oil palm sector is also due to the critical versatility deriving from the contemporary production of two different oils: Crude Palm Oil (CPO)—extracted from the pulp of the fruit—and Crude Palm Kernel Oil (CPKO)—extracted from the kernel -, which, after the refining process, are mainly used as cooking oil or as an ingredient for industrial food products, for energy products (especially biofuels) or to produce cosmetics and detergents for household cleaning. Moreover, the "Cake of Palm Kernel", a commonly used ingredient for animal feeds, is obtained from the crushing of the palm fruit kernel (EC 2018, EPOA, IDH, RSPO, 2022).

Despite huge regional differences, it is estimated that around 60–75% of globally produced palm oil is used in the food sector, 20–30% in home and personal care, and 5–10% in the energy sector (WWF 2016; Pacheco et al. 2017; Voora et al. 2020). Between 2008 and 2018, EU palm oil imports used for food and oleochemicals declined heavily (-32.5%), but this reduction was accompanied by a steep increase in consumption related to the energy sector (ca./c. + 80%) (Murphy et al. 2021). More specifically, between 2010 and 2014, the EU's consumption of palm-based biodiesel increased by 500% (Transport&Environment, 2016a; b). Consequently, since 2018, up to 69% of European palm oil consumption has been linked to private and commercial transport—53 to 55% -, electricity, and heating systems—12 to 14%—(Transport&Environment, 2019).

Among EU member states, Spain, rapidly becoming the leading EU player in the sector, accounts for 44% of the European palm oil biodiesel production. Currently, up to 90%—versus an average 33% in the EU—of the Spanish biofuel sector—the seventh largest at the global scale—is supplied with palm oil (Transport&Environment 2017, 2018; El Confidencial 2019).

Besides the energy sector, other sectors play a relevant role in palm oil consumption. According to Brack et al. (2016), in Western Europe, at least 50% of industrial products in the "food", "household cleaning" and "cosmetics"—up to 70%—(CosmeticsDesign-Europe 2014) sectors contain palm oil derivatives.

Research focus and questions

Since in Cuypers et al. (2013) the embodied deforestation concept was used to link deforestation to EU consumption, research has mainly been carried out at a global or regional scale, encompassing multiple FRCs. However, in the context of physical

[6] The sector includes nine main oils i.e., palm, soybean, rapeseed, sunflower, palm kernel, groundnut, cottonseed, coconut, and olive oils.

[7] According to the European Commission (EC 2018), to completely replace palm oil production with alternative vegetable oils, area harvested should be increased by five to eight times.

accounting approaches, single country-based analyses, focussing on a few importing and producing countries, and targeting one product are largely missing.

Therefore, the focus of this study is to investigate the palm oil imports by four EU countries (Germany, France, Italy, and Spain), between 2000 and 2019, from Indonesia, Malaysia, and PNG and the associated LUC embodied impacts. Since, over the assessment period, Germany, France, Italy, and Spain have been representing 57% and 66% of respectively the average EU27's population and Gross Domestic Product (GDP) (Eurostat 2022), they allow catching a large share of the overall impacts embodied in the EU consumption of palm oil.

More specifically, this work aims to address, for the selected importing countries, the following research questions:

(1) How is the palm oil trade network shaped? Are there major direct trade links with producing countries or intermediate trade partners?
(2) What proportion of palm oil imports is driven by the food, olechemicals and energy sectors?
(3) How much land footprint is associated with palm oil imports?
(4) How much deforestation, and CO_2 emissions associated with LUC activities are embodied in the palm oil consumption?

The paper is structured as follows: the first section, i.e., this section, introduces the research topic, the state-of-the-art in literature, the problem statement and the research questions. Within the second section, the materials and methods used for the study to quantify the embodied impacts driven by the demand for palm oil by the four selected EU countries are provided. Impacts are reported, together with other results, within the third section. The fourth section discusses results and main limitations with possible ways forward (4.1) to improve research in this field. Finally, the fifth section draws general conclusions.

Materials and methods

Our methodology was inspired by environmental accounting methodologies (Tukker et al. 2016), global consumption-based land-use accounting (Bruckner et al. 2015), and physical accounting models (De Laurentis et al. 2022), which are aimed to assess international trade as an indirect driver of social and environmental impacts.

More specifically, physical accounting models for assessing commodities supply chains are characterized by two main stages: (1) the analysis of primary production and processing at the country level, and (2) the bilateral trade analysis or network analysis of trade (Bruckner et al. 2015). The first stage regards the attribution of land use (e.g. hectares of croplands) to a primary product or processed commodity in the country of production through specific conversion coefficients (e.g. crop yields and extraction rates). The second stage focuses on tracking, along the global network of trade, the products expressed in physical inputs (e.g. land, water, carbon) from the country of production to the one of apparent consumption (i.e. imports–re-exports) (Bruckner et al. 2015).

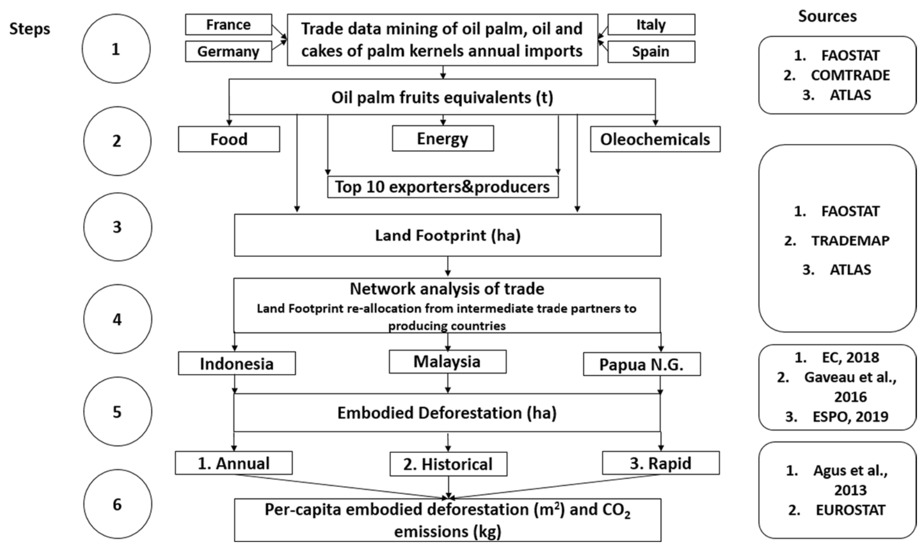

Fig. 1 Flowchart of the applied methodology

One of the main limitations of bilateral trade analysis is the low capacity to detect the different positions and functions of the nodes (i.e. trade partners) within the trade network (Sun et al., 2023). To overcome this limitation, a network analysis of trade can represent a strategy to recognize possible trading intermediaries representing “major regional re-export hubs” (West et al., 2022).

In this context, our six-steps methodological framework links trade flows in physical quantities to virtual biophysical inputs (i.e. hectares of agricultural lands and tropical forests, tonnes of CO_2 emissions virtually incorporated in global trade) needed to meet the annual consumption demand within importing countries, thus quantifying the embodied deforestation footprint and embodied CO_2 emissions associated to agricultural LUC activities—performing a so-called land use impact assessment[8]—(Hayashi, 2018) within specific producing countries.

Figure 1 visualizes the framework and the key data sources - e.g., FAOSTAT, COMTRADE (2022), ATLAS of economic complexity (2022), TRADEMAP (2022) - associated with each step.

Within the Additional file 1, a more detailed description of the methods used to quantify the physical quantities of primary crop equivalents, as well as the land footprint and related embodied, impacts, is provided.

Step one (1): trade data mining and cleaning

Between 2000 and 2020, annual imports of palm oil, oil of palm kernels, and cakes of palm kernels by the four selected EU countries have been considered. Trade flows data in volume were gathered from FAOSTAT (our main trade data source) and compared with the COMTRADE dataset (as for quantities), and from the "ATLAS of Economic Complexity” (as for monetary values). As a general rule, bilateral trade data were collected

[8] In Life Cycle Analysis (LCA) is the part of the study dealing with the environmental impacts caused by anthropogenic activities (e.g. deforestation and peatland drainage) carried out before the start of bio-commodities production.

considering the annual volumes reported by the country of import. Afterward, the total annual imports by the four EU countries of the three commodities from (to) the Rest of the World (ROW) have been converted into tonnes of primary crop equivalents (i.e., oil palm fruits), by using the formula of Cuypers et al. (2013) and De Laurentis et al. (2022) and a specific conversion factor from FAO (2011) to convert palm kernels into oil palm fruits (Additional file 1).

Step two (2): consumption by economic sector and exporters ranking

The crop primary equivalent imports have been split up into three economic sectors: food (feed), energy (industrial), and oleochemicals (industrial), and the ranking of the top ten palm oil direct trade partners of palm fruits equivalent (eq.) have been assessed.

In order to quantify the share (%) by sector over the total value of imports of each importing country, statistics, differentiated per country of primary production (i.e. direct export), were gathered through the TRADEMAP platform of the International Trade Center (ITC). All the data and results specific to the three economic sectors cover the period between 2004 and 2020. This period was chosen because of missing data for Germany before 2004. Additional file 1 provides a description of the allocation method and related assumptions.

Step three (3): land footprint estimation

The annual primary crop equivalent imports per direct trade partners were converted into hectares of oil palm plantations needed for production. Annual yields (t/ha of oil palm fruits) per country of production were obtained from FAOSTAT. In order to avoid the influence of possible bias within the time series of annual yield data per country of production/trade partner, we decided to calculate a five-year rolling mean and, thus, the times series of the smoothed yield data (Additional file 1). In the case of intermediate trade partners, the average of the annual five-year rolling mean was used.

After step 3 for each EU importing country, we obtained the dataset of the annual land footprint embodied, between 2000 and 2020, within the imports of the three processed agricultural commodities from direct trade partners, namely both producing countries of oil palm fruits and crude oil exporting directly within the four importing countries and intermediate trade partners just re-exporting these products.

To assign the land footprint only to global producing countries the step 4 has been implemented.

Step four (4): trade network analysis

The hectares of land footprint both directly and indirectly exported by the three main producing countries—i.e., Indonesia, Malaysia, and PNG—to the four EU importing countries, were specifically detected. To this purpose, a more in-depth analysis of the primary crop equivalents global trade network was performed. For each of the four EU importing countries, the annual land footprint values assigned in step 3 to producing and non-producing countries (i.e., intermediaries) were assessed and partially reallocated. To do so, we compared the annual land footprint and the annual area harvested within each trade partner. If the annual land footprint was higher than the area harvested, the difference between this quantities—"extra land footprint"—was re-allocated to the country of production. The re-allocation method is based on the assumption that each annual amount of extra footprint can be allocated in percentage—by calculating trade shares—to each of the direct trade partners of the three commodities of the EU intermediate trade partner. The reallocation process terminates when no more extra-footprint is detected in the model.

Once all the hectares of land footprint were assigned to the production countries, we obtained the annual land footprint time series in Indonesia, Malaysia, and Papua New Guinea.

In order to obtain a measure of the net annual land footprint by country of export, we also subtracted from the previous values the hectares of land footprint embodied in the re-exports to ROW of oil palm fruits eq. by the four EU countries. To quantify the annual re-exported number of hectares cultivated within the three producing countries, we applied the share (%) of the total annual land footprint imported from each of them. From the time series of the net annual land footprint, we then calculated the net annual import of primary crop equivalent through the inverse of the formula already used in Step 1.

Finally, the mean annual land footprint and the minimum and maximum values of land exploited over the whole period by the four importing countries within each of the producing countries were computed.

Step five (5): embodied deforestation

Concession-level approach

We conducted embodied deforestation estimates by first considering a concession-level approach. To this aim, the annual values of land footprint, per sector and country of export, have been multiplied by the Annual Deforestation Intensity (ADI), which corresponds to an estimate of the annual deforestation rate within the active palm oil concessions in the three producing countries. The ADI (Table 4) was determined as an average value among the ones reported in Table 1, which were quantified (see Additional file 1) from five studies regarding yearly forest loss, between 2000 and 2016, over active production areas in Indonesia, Malaysia, and PNG categorized by country

Table 1 Annual forest loss (%) within RSPO certified (2008–2016) and conventional plantations (NO-RSPO) (2000–2016)

References	Time period	Countries	Annual forest loss rate (%)	
			RSPO (2008–2016)	NO-RSPO (2000–2016)
Meijaard et al. (2017)	2000–2015	Indonesia-Malaysia	0.4	0.9
Gunarso et al. (2013)	2001–2010	Indonesia—Malaysia—P.N.G	n.a	0.15–0.3–0.02
Austin et al. (2017)	2000–2015	Indonesia	n.a	0.13
Cazzolla Gatti et al. (2019)[a]	2001–2016	Indonesia—Malaysia—P.N.G	2.70	2.42
Carlson et al. (2018)	2000–2015	Indonesia	0.11	0.12

[a] This study provides higher values of the annual deforestation rate because performing a more refined analysis—i.e. at company-level—of deforestation trends within RSPO and NO-RSPO palm oil plantations

n.a. not available

and type of plantations (i.e., conventional or Round Table for Sustainable Palm Oil—RSPO—certified). RSPO, the leading certification scheme in the palm oil sector (Jafari et al. 2017), which has been labelling certified sustainable palm oil since 2008, has reached around 19% of global production (RSPO 2021). The ADI was applied differently to the estimated share of RSPO production areas and the one of conventional plantations (NO-RSPO). For the former, the ADI was applied only to the share of plantations associated with the production destined to the food sector, as these are the only ones for which reliable data is available regarding the proportion of RSPO certified products imported by the four European countries. Shares (%) quantified in step 2 were used to attribute the land footprint values to sectors and countries of production. Data on certified palm oil imports for the four EU countries were mostly retrieved from the European Sustainable Palm Oil (ESPO) progress report (2019). Since only data for specific years (i.e. mainly from 2013 onwards) were available, it was decided to estimate missing values, before 2013, by using a precautionary value equal to 50% of the closest known value. On the other hand, when the missing value was between two known values, the median was used. In order to estimate the total and mean annual deforestation embodied in the oil palm fruit eq. net consumption and to avoid potential double counting, we firstly set a baseline of palm oil production areas (ha) in the first year (i.e. 2004), and then we added only annual production area increments, while setting to nil any eventual annual negative values (e.g., a yearly decrease of production areas—i.e. land footprint—embodied in the consumption of oil palm fruits eq. in Europe).

Historical approach

The second approach considers a longer interval of LUC processes linked to palm oil production in Indonesia, Malaysia, and PNG, based on the hectares of historical deforestation. For this assessment, we used a specific historical deforestation rate—Table 2—(Vijay et al. 2016) as an indicator of the deforestation risk historically (i.e. deforestation activities associated with palm oil production since 1989) characterizing palm oil plantations in the three producing countries. This indicator is one of the most recognized indicators to quantify the historical impacts of palm oil production within the targeted countries (see e.g., EC 2018).

Table 2 Share (%) of historical and rapid deforestation embodied within palm oil plantations after 1989 per country of production

Share of deforestation/country	Indonesia	Malaysia	Papua New Guinea
Historical	53.8	39.6	25.3
Rapid	11.0	8.1	5.2

Rapid-conversion approach

The same method but considering deforestation rates derived from Gaveau et al. (2016) has been adopted to investigate the concept of rapid conversion—i.e. deforestation carried out within 5 years before the start of palm oil fruits production activities—and to quantify the third measure of embodied deforestation. Rapid conversion coefficients (Table 2) (i.e., 20.5% of the historical deforestation rates) were applied to the annual values of the land footprint of the three exporters.

Overall, we obtained three measures of embodied deforestation, i.e. 1) the concession-level approach, 2) the historical approach, and 3) the rapid conversion approach. For the first appraoch, results were also distinguished into the main three economic sectors of destination.

Step six (6): per-capita deforestation footprint and per-capita embodied carbon dioxide emissions

We divided yearly estimates of embodied deforestation by the resident population in each importing country (Eurostat 2022). CO_2 emissions data from Agus et al. (2013a) were used to estimate carbon dioxide emissions embodied within palm oil imports by targeted importers. Estimated emissions (57tCO_2/yr/ha) including Above Ground Biomass (AGB) reduction, fires, and peatland conversion—during the period 2000–2020 in the three producing countries, have been multiplied by the annual values of embodied deforestation (ha) of each approach. Finally, the total and average annual per-capita CO_2 emissions (kg) were estimated for the resident population within the four EU importing countries.

Results

Trade flows of primary crop equivalents

The top ten primary crop equivalents direct trade partners (including both producing and non producing countries) serving the EU market for Italy, France, Germany, and Spain are respectively shown in Figs. 2 and 3.

Between 2000 and 2020, Indonesia played a considerable role in terms of direct export of primary crop eq. to all four EU countries, particularly to Italy (57.5%) and Spain (57.1%). Malaysia instead was the second-largest direct partner for Italy (20.9%) and Spain (12.7%) and the third for the other two countries (9–12%). Papua New Guinea was the third-largest direct partner for Spain (7%) as well as the fourth for Germany (6%) and Italy (4.8%). If we look at the whole list of trading partners, different trade profiles have emerged from the analysis among the four EU importing countries. Italy, for instance, shows a major (87%) direct trade link with South-East Asia producing countries, while France and Germany reveal a greater direct trade link (72 and 45% respectively) with non-producing countries (mainly the Netherlands). Moreover, Germany and Spain show a considerable direct link (7 and 12% respectively) to Central-South American producing countries.

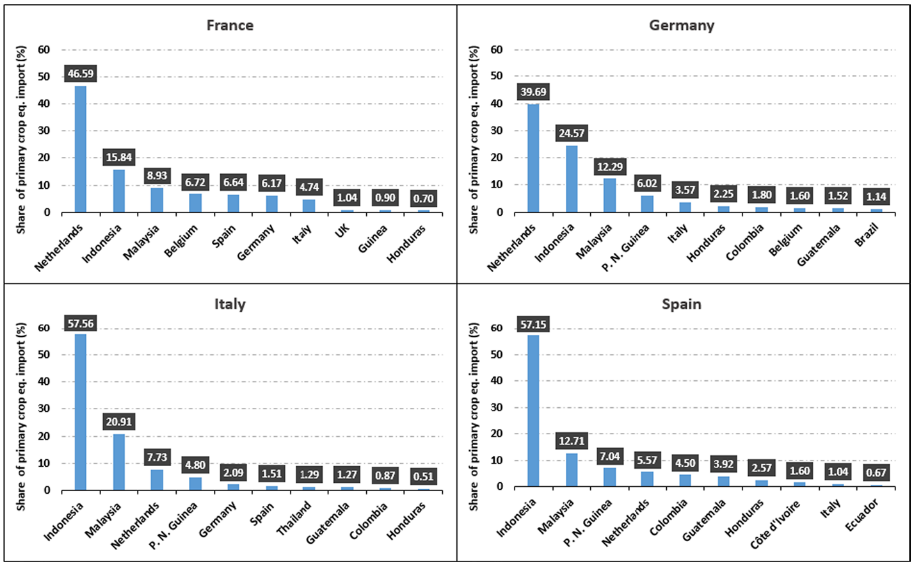

Fig. 2 Share (%) of primary crop equivalent import from the top ten direct trade partners for the period 2000–2020. Own elaboration from FAOSTAT data

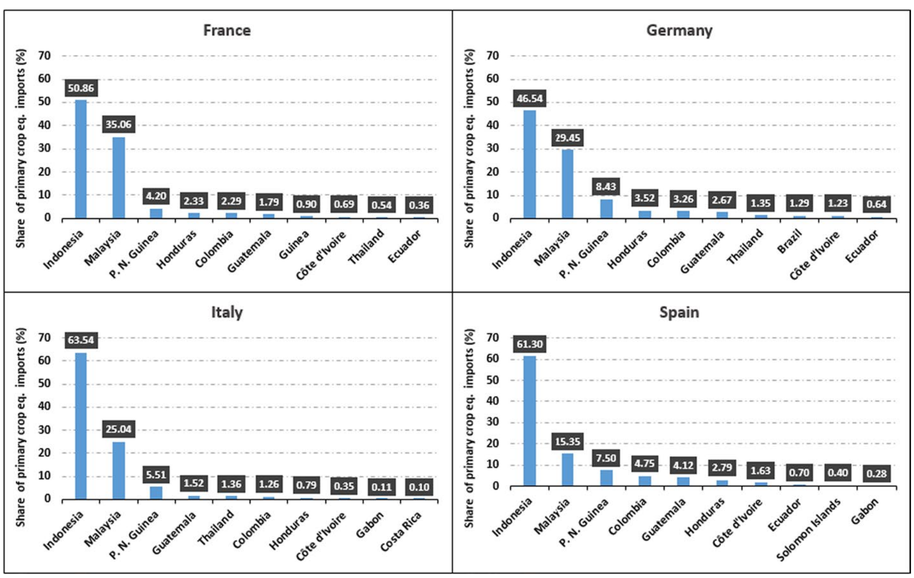

Fig. 3 Share (%) of primary crop eq. (direct and indirect) imports from the top ten trade partners (and producing countries) for the period 2000–2020. Own elaboration from FAOSTAT data

Figure 3 highlights the differences in the results if the trade network of intermediate trade partners (i.e., not producing countries) is assessed, and the primary crop eq. are re-allocated into global producing countries of oil palm fruits, which are in turn direct trade partners of the intermediate trade countries.

After the re-allocation, Indonesia becomes the main trade partner for all the EU countries, Malaysia the second and PNG the third.

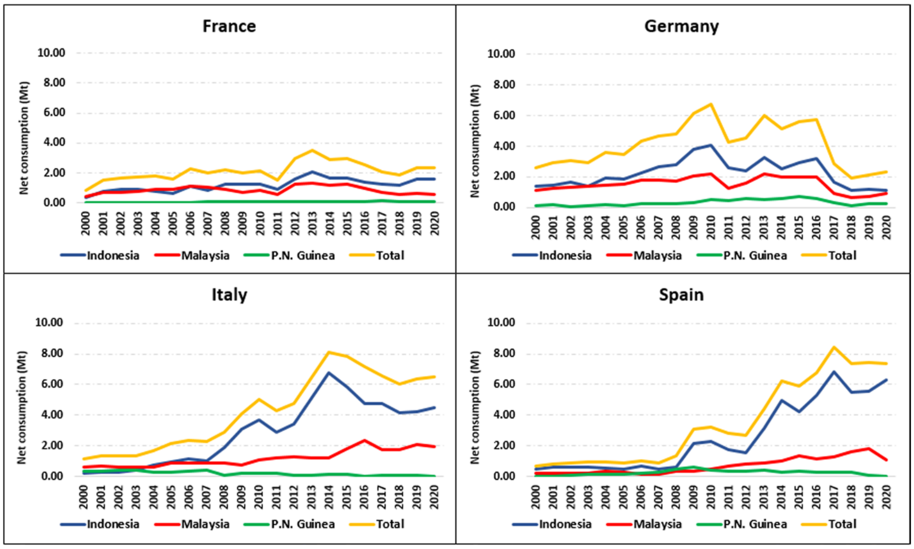

Fig. 4 Net consumption (imports–re-exports) per country of production of primary crop eq. Source: own elaboration from FAOSTAT data

As underlined in the previous sections, a complete picture of trade dynamics is of primary importance for tracing the indirect trade flows of palm oil. Therefore, through calculations made within step 4 of our methodology, we could assess the evolution over time of the sum of both direct and indirect imports of primary crop eq. for each of the four EU importing countries (Fig. 4).

From 2000 to 2020, Italy directly and indirectly imported around 89.6 Mt of oil palm fruits eq. from production areas located within Indonesia, Malaysia, and PNG. The greatest increase (+ 119%) occurred between 2007 and 2010, followed by a drop in 2011, and a second increase (+ 89%) until 2014, which corresponds to a peak in Italy's primary crop eq. net consumption. The first sudden growth in Italian net-consumption of oil palm fruits eq. was mainly due to the parallel increase of the Italian and the Netherlands (the main Italian intermediary) direct imports of palm oil from Indonesia by + 350% and + 50%, respectively. Until 2003, Malaysia was the main trade partner for Italy, while between 2004 and 2020 most of the Italian imports were sourced from Indonesia. Nevertheless, since 2015, the decrease the imports from Indonesia has corresponded to a rise in Malaysian's share.

Instead, France has imported around 45.1 Mt of oil palm fruits eq. with the greatest increase (+ 123%) between 2011 and 2013. Besides a general increase in the direct imports from Indonesia (+ 30%) and Malaysia (+ 38%), the increase was due to the re-exports effect from the Netherlands (+ 43% direct imports from Indonesia and + 37% from Malaysia), which was respectively the intermediary of 47% of the French direct imports (Fig. 2). Overall, French imports for products coming from Indonesia and Malaysia show a fluctuating trend over the entire period considered.

Germany has imported around 86 Mt of oil palm fruits eq., showing a waving trend in the trade patterns: a general increase in the first period (+ 93% between 2005 and 2010), followed by a first steep decrease (− 36%) between 2010 and 2011, a period of stability between 2012 and 2016, followed by a second strong decrease (−67%) between 2016 and 2018. Behind the first decrease was the sum of the lowest German direct imports from Indonesia, Malaysia, and the Netherlands, and the drop of Netherlands direct imports from Indonesia and Malaysia. On the other hand, the second decrease was mainly due to the decreasing trend of the German direct imports from Papua New Guinea (−100%), and the parallel decrease in the German direct imports from the Netherlands (−67%).

Spain imported around 74.2 Mt of oil palm fruits eq., showing the slowest trend among the four EU countries until 2007, when imports from all the three producing countries started to increase—at a different rate—until 2017. Concerning the net consumption of Indonesian oil palm fruits equivalent, three distinct periods of sharp increase can be detected. Firstly, between 2007 and 2010, when the direct imports from Indonesia increased by 155%, and secondly, between 2011 and 2014, by 181%.

Net consumption of oil palm fruits equivalents by sector

Figure 5 reports the net consumption of oil palm fruits eq. by sector of destination within the four EU importing countries.

In Italy, until 2009, the food sector had a major role, while since 2010, the energy sector became the leading sector. Between 2012 and 2015, the net consumption of oil palm fruits eq. allocated to the energy sector in Italy registered a boom (+155%). Regarding France, while imports for the food and oleochemical sectors remained, with slight variations, almost constant and very low over time, those for the energy sector, covering the major share, showed a much more fluctuating trend, with a steep increase (+125%) between 2011 and 2013, followed by a rapid decrease (−76%) between 2013 and 2018. The analysis for Germany clearly shows that the decline in imports started from 2010 has been mainly due to variations in imports destined for the food sector. On the other hand, regarding Spain, the general rising trend observed between 2007 and 2017 (Fig. 5) has been primarily linked to the growing demand associated with the energy sector (i.e.

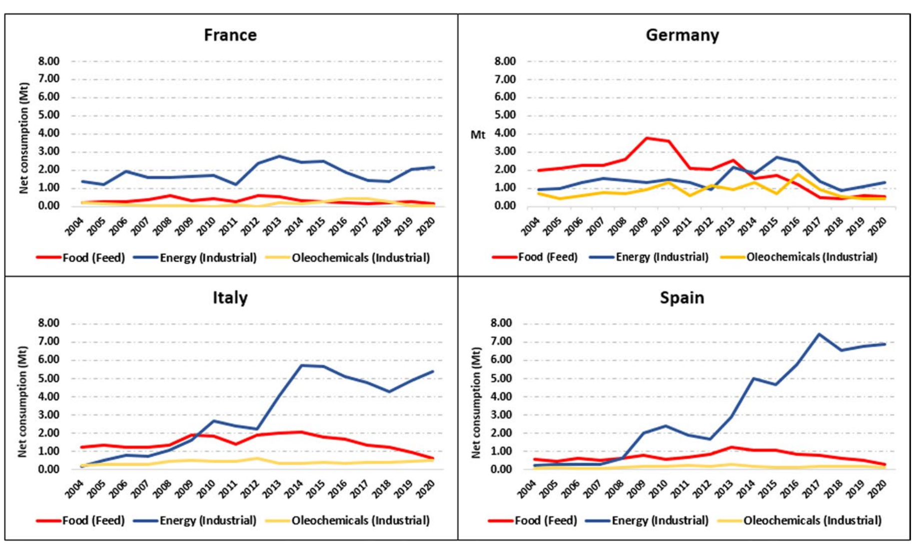

Fig. 5 Net consumption (Mt) of palm fruits eq. by sector. Source: own elaboration on TRADEMAP

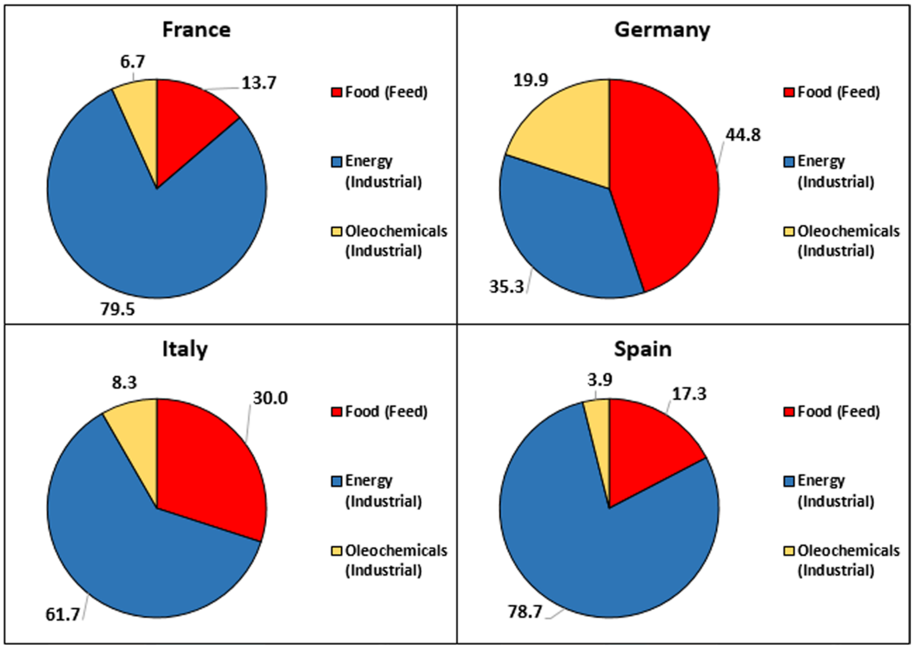

Fig. 6 Average data (2004–2020) on imports by sector (%). Source: Own elaboration from FAOSTAT and TRADEMAP data

biofuels production), mainly fed by Indonesian products. Figure 6 shows the average share of imports by macro-economic sector.

As already detected in Fig. 7, on average, French, Italian and Spanish imports of oil palm fruits eq. were mostly allocated to the energy sector. On the other hand, Germany has been the country where oil palm fruits eq. have manly (44.8%) served the food sector. Moreover, Germany, showing a more heterogeneous allocation trend, have destined a consistent share (19.9%) to the oleochemicals sector. These can represent pivotal information when assessing which commodities, within each

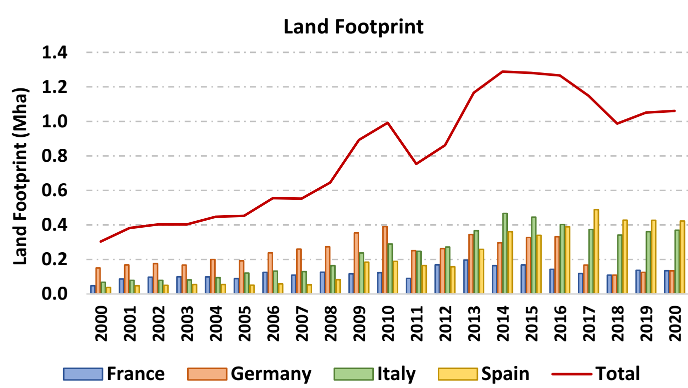

Fig. 7 Total annual land footprint (Mha)—red line—and annual land footprint by country of net-consumption—vertical bars -, between 2000 and 2020. Source: own elaboration from FAOSTAT data

country of imports, might be, more or less, implicated in controversial sustainability impacts.

Embodied impacts

Land footprint

The trend of embodied land footprint among the four importing countries is shown in Fig. 7. Furthermore, the mean annual, minimum, and maximum land footprint values

Table 3 Mean annual and minimum and maximum values (ha) of embodied land footprint by country of production (2000–2020)

	Mean annual	Min–Max
Italy		
Indonesia	165,793	[9940 (2000)–394,518 (2014)]
Malaysia	64,451	[33,403 (2003)–123,054 (2016)]
Papua New Guinea	13,720	[2307 (2020)–28,091 (2002)]
Total	243,963	[68,029 (2000)–466,790 (2014)]
France		
Indonesia	68,710	[21,072 (2000)–119,422 (2013)]
Malaysia	47,029	[24,604 (2000)–70,587 (2013)]
Papua New Guinea	5664	[1821 (2000)–10,068 (2017)]
Total	121,404	[47,497 (2000)–196,248 (2013)]
Germany		
Indonesia	129,124	[66,326 (2018)–237,041 (2010)]
Malaysia	82,166	[34,702 (2018)–118,091 (2010)]
Papua New Guinea	22,973	[4922 (2002)–51,897 (2015)]
Total	234,263	[109,016 (2018)–390,141 (2010)]
Spain		
Indonesia	150,465	[23,881 (2005)–398,334 (2017)]
Malaysia	36,983	[8239 (2006)–97,417 (2019)]
Papua New Guinea	17,352	[991 (2000)–41,151(2009)]
Total	204,800	[37,452 (2000)–488,258 (2017)]

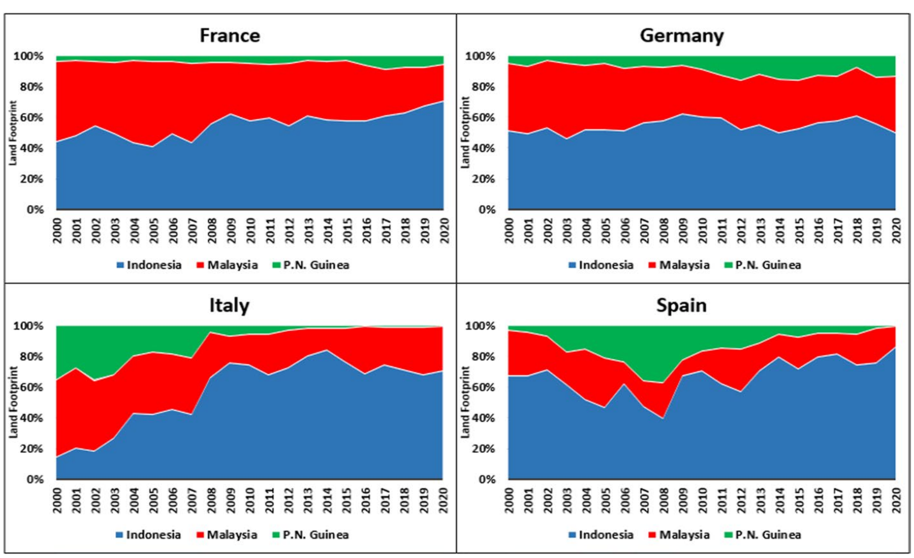

Fig. 8 Share (%) of land footprint by country of production between 2000 and 2020

(ha) by country of import and reference year—within brackets—recorded during the period are shown in Table 3. Finally, Fig. 8 reports the share of land footprint by country of production between 2000 and 2020.

Three different periods characterizing the trend of the embodied land footprint can be detected in Fig. 7. The first period, between 2000 and 2011, led by Germany, the second period, between 2012 and 2016, led by Italy, and the third period (2017–2020), in which Spain took the lead.

Besides the peak reached in 2014 (1.29 Mha), two main periods of embodied land footprint growth can be identified. The first occurred between 2007 and 2010 (+ 80%), and the second (2011–2014), in which the overall impact increased by 71%.

Italy reached a peak in 2014 with 466,790 ha, being the country, among the four EU importers, that impacted on average the most in terms of land footprint and that outsourced the largest average annual palm oil production area in Indonesia (165,793 ha). France reached a peak in 2013 (196,248 ha) and, among the four countries considered, it is the one with the lowest impact in terms of land footprint. Germany outsourced the largest land footprint value in 2010 (390,141 ha) and embodied the largest average amount of palm oil production areas located in Malaysia (82,166 ha) and PNG (22,973 ha). Spain reached an annual peak (488,258 ha) in 2017, being the country showing the largest yearly land footprint value (398,334 ha) referred to Indonesia. Overall, on average, between 2000 and 2020, 0.8Mha/yr—Indonesia (64%), Malaysia (29%), and PNG (7%)—of oil palm plantations have been embodied in the annual net consumption of palm oil fruits equivalents by the four importing countries.

Embodied deforestation

The results on embodied deforestation for the three different approaches, i.e. concession-level, historical and rapid-conversion, calculated according to step 6 of our methodology, are presented below.

The considerable differences among the shares of deforestation linked to oil palm fruits production in each producing country for the three approaches (Tables 4 and 5) are due to the time span considered and some different theoretical assumptions. Indeed, the historical and rapid shares encompass 1990's deforestation rates which were significantly higher than those registered in South-East-Asia between 2000 and 2020 (FAO 2020), which are used in the first approach. Furthermore, the three approaches represent

Table 4 Mean annual deforestation intensity (ADI)—%—by country of export and by type of plantation

Country	Average (2008–2016) RSPO concessions (%)	Average (2000–2016) conventional concessions (%)
Indonesia	1.07	0.74
Malaysia	1.55	1.25
Papua New Guinea	2.71	1.22

Since the values within Table 4 were quantified from input data referring to different periods and production areas and quantified through distinct methodologies and assumptions, they cannot be considered general results about the comparison among deforestation trends within RSPO and NO-RSPO concessions. Moreover, to compute the NO-RSPO mean annual rate we used a larger set of data (see Table 2)

Table 5 Total (ha) and mean annual—within brackets—(ha/yr) embodied deforestation for the Historical and Rapid deforestation approaches per country of production (2000–2020)

Approaches	Historical Embodied Deforestation (ha)				Rapid Embodied Deforestation (ha)			
Country	**Indonesia**	**Malaysia**	**PNG**	**Total**	**Indonesia**	**Malaysia**	**PNG**	**Total**
France	106,216 (5058)	45,942 (2188)	4,288 (204)	156,446 (7450)	21,774 (1979)	9418 (448)	879 (42)	32,071 (1527)
Germany	190,703 (9081)	71,048 (3383)	19,566 (932)	281,317 (13,396)	39,094 (1862)	14,565 (694)	4011 (191)	57,670 (2746)
Italy	243,172 (11,580)	63,410 (3020)	12,910 (615)	319,493 (15,214)	51,555 (2455)	12,999 (619)	2647 (126)	67,200 (3200)
Spain	297,084 (14,147)	47,049 (2240)	14,455 (688)	358,587 (17,076)	60,902 (2900)	9645 (459)	2963 (141)	73,510 (3500)

distinct conceptual perspectives for interpreting the link between current palm oil production and past deforestation activities. The concession-level approach, for instance, considers only the yearly logging activities (annual % of deforestation over total forest cover) carried out within the active concessions in each country of production to expand the oil palm harvested area between 2000 and 2016. While instead, the second and the third approaches attribute to palm oil production the logging activities that have been falling within two different kinds of temporal intervals, namely, all the deforestation that occurred between 1989 and 2020—historical approach—and the deforestation that, between 1989 and 2020, has been carried out within five years before the start of oil palm fruits harvesting—rapid approach -.

Given these differences in the underlying statistics, the results of the first approach cannot be compared with those of the historical and the rapid perspectives.

Concession-level approach

Data on annual forest loss within RSPO certified concessions (2008–2016) and conventional plantations (2000–2016) have contributed to the estimates reported in Table 1, which were further elaborated in order to obtain a mean yearly proportion of forest loss

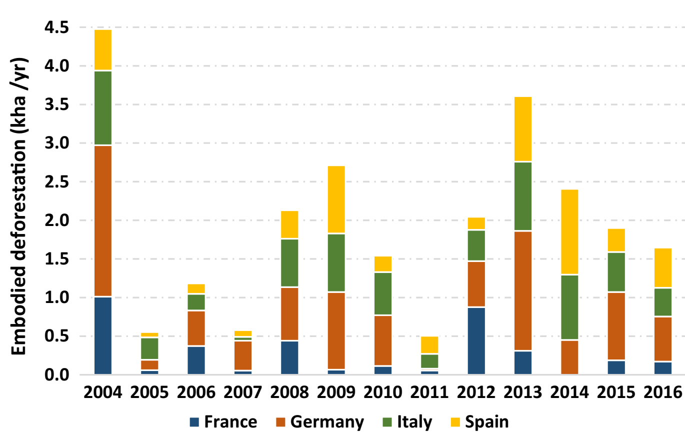

Fig. 9 First approach: Annual embodied deforestation (kha)

by country of export and by type of plantation (i.e., RSPO-certified and conventional) as reported in Table 4.

According to Fig. 9, between 2004 and 2016, Germany has been the country with the greatest impact in terms of embodied deforestation at concession-level (9383 ha).

Italy ranks second (6699 ha) followed by Spain (5477 ha) and by France, which shows the lowest embodied deforestation at concession-level (3726 ha).

On average, between 2004 and 2016, the four countries have imported 1945 ha/yr of tropical deforestation.

Historical and rapid-conversion approaches

Table 5 summarizes the results for the historical and rapid approaches per country of origin and destinations.

According to the second and third approaches, Spain is the country that embedded the larger estimates of historical and rapid-conversion deforestation, being the country with the larger impact in Indonesia. On the other hand, Germany showed the larger impact both over Malaysian and Papua New Guinea's tropical forests.

Embodied deforestation by sector

The results related to the allocation of the first-approach embodied deforestation to the three economic sectors of net consumption are summarized in Table 6 and Fig. 10.

Table 6 Total annual (ha) and mean annual—in brackets—(ha/yr) embodied deforestation at concession-level by macro-economic sector (2004–2016)

Sector/country	Italy	France	Germany	Spain
Food	2781 (214)	1076 (83)	5126 (394)	1631 (125)
Energy	3382 (260)	2660 (205)	2378 (183)	3071 (236)
Oleochemicals	535 (41)	390 (30)	1879 (144)	268 (21)

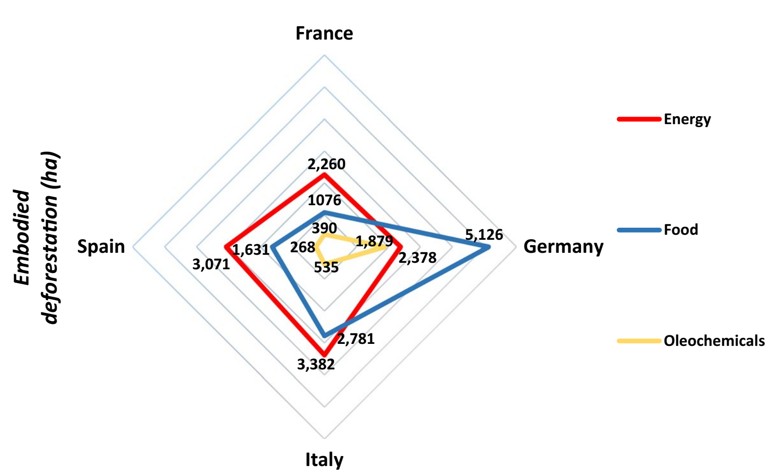

Fig. 10 Total concession-level embodied deforestation (ha) by macro-economic sector. Own elaboration from several sources (see Fig. 1)

Table 7 Total per-capita embodied deforestation (m^2) and CO_2 emissions (kg) for the concession-level (2004–2016), the historical and the rapid approaches (2000–2020)

Approach/country	Italy	France	Germany	Spain
Per capita embodied deforestation (m^2)				
Concession-level	1.1	0.6	1.1	1.2
Historical	55.4	24.6	34.4	78.1
Rapid-conversion	11.3	5.0	7.0	16.0
Per capita embodied CO_2 emissions (kg)				
Concession-level	6.4	3.3	6.5	6.8
Historical	315.5	140.0	195.9	445.0
Rapid-conversion	64.7	28.7	40.2	91.2

The German food sector is the one that embodied the larger deforestation footprint (5126 ha) followed in order by the Italian (3382 ha), and the Spanish (3071 ha) energy sectors.

Per-capita embodied deforestation and CO_2 emissions

Results in terms of per-capita embodied deforestation and associated CO_2 emissions are presented in Table 7.

In the concession-level approach, between 2000 and 2016, each Italian and German citizen consumed about 1.1m^2 of tropical forests in Indonesia, Malaysia, and Papua New Guinea through their consumption of palm oil, oil of palm kernel and cakes of palm kernel, thus contributing to the emission of respectively 6.4kgCO_2/per-capita and 6.5kgCO_2/per-capita of LUC-related carbon dioxide (Table 7).

A greater impact was annually produced by Spanish citizens (1.2m^2/per-capita and 6.8 kg/per-capita of CO_2), while much lower values are associated with French (0.6m^2/per-capita and 3.3 kg/per-capita of CO_2) citizens.

If historical deforestation trends are considered, the Spanish citizens are widely ranking first (78.1 m^2/per-capita and 444.9 kgCO_2/per-capita), while when rapid forest conversion is considered German and French citizens have widely consumed respectively less than half of tropical forests embodied by the Spanish economic sectors.

Discussion

The growing polarization of the World's palm oil production resulting from a steep increase in LUC processes has determined profound socioeconomic and ecological effects (Qaim et al. 2020).

Globally, between 1961 and 2019, oil palm plantations have increased from nearly 3.6 Mha to 28 Mha. In the same period, Malaysia and Indonesia increased their oil palm harvested areas from 0.113 Mha to 20 Mha, equivalent respectively to 52% and 18% of the global palm oil production areas in 2019 (Faostat, 2021). As a result, the two countries became the production and export base for about 90% of palm oil consumed worldwide (EC 2018).

In this context the EU has represented the final destination of around 20% of the total palm oil exports produced in Indonesia and Malaysia, becoming the leading consumer at a per-capita level.

The general aim of this study was to quantify and compare few specific environmental impacts embodied in the palm oil net-consumption of the main EU economies and address four specific research questions (Sect. 1).

With reference to the first research question, our analysis has found significant differences in the composition of the trading partners (Figs. 4 and 5) and the overall trend of imports (Fig. 6) among the EU countries of interest. For instance, we have seen how Italy and Spain showed prominent trade links with producing countries while France and Germany depended more on intermediate trade partners. The role of the Netherlands, for example, is particularly relevant, possibly because of the trade logistics and internal processing capacity of crude palm oil (Altenburg et al. 2021). As an outstanding case, six vegetable oils and fats refineries in the port of Rotterdam make the port—the largest in the EU pertaining to the total volume of cargo storage (Sandströma et al. 2018)—a major player in the large-scale refining, processing, storing and supplying of edible oils to the European food industry. Therefore, we can assume that north-west European countries have more intra-EU trade networks, highly depending on large northern ports like Rotterdam, Amsterdam and Hamburg and their associated gateway regions (Notteboom 2010; Rodrigue et al., 2010), and south European countries still conserve a direct trade network with South-East Asia through the Mediterranean.

The results (Fig. 6) also indicate that while Italy, France, and Spain have faced a general increase in their net-consumption (i.e. imports) over the period, Germany, which was the first among the four countries to have reached a peak of nearly 6.7 Mt of net imports in 2010, has then showed a steep decrease of palm oil net consumption (−67% between 2016 and 2018). The reasons behind this trend in Germany could be related to the substitution with alternatives (e.g., sunflower oil) driven, for instance, by price effects within the food sector. According to Antonarakis et al. (2022), for example, after the 2008/2009 Global Financial Crisis, an increase in the palm oil price has contributed to determining peculiar effects on the supply and demand at the regional and global levels. On the other hand, it is worth considering that, in Germany, the already mentioned (Sect. 1) EU's shift in the allocation of palm oil from the food to the energy sector has probably played a minor role due to its leading position in global rapeseed oil production. For instance, between 2000 and 2020, Germany has been, after China, the world's second-largest producer of rapeseed oil (13% of the global share) (Faostat 2022), which, consequently, represents the dominant oilseeds feedstock in Germany and France for production of first generation biofuels (BMWi 2017, The Digest, 2018). Therefore, the role of rapeseed oil, as the main alternative to palm oil as a feedstock for energy products, may be considered one of the main reasons behind the broad differences in the import patterns, reported in Fig. 6, between the central and the south-Europe countries. Considering the ratio between the consumption of the palm oil produced in Indonesia and Malaysia, it is visible how, in 2007, Indonesia made its leap as the leading palm oil producer and exporter for all the European partners (Fig. 6).

Furthermore, according to our trade networks analysis, the fluctuating trends shown in Fig. 6 can be explained by the increasing or decreasing volumes of direct trade of the four targeted EU countries from each producing country but also by those of the main trade intermediaries. For instance, if the Netherlands increases its imports from Indonesia, Malaysia, and PNG, this reflects in a cascade effect incorporated within the Netherlands' palm oil re-exports (i.e. indirect trade) to France, Germany, Italy, and Spain.

Regarding the second research question, data for Italy, Germany and Spain show that, following different trends, leading consumption sectors have shifted from the food sector towards the energy sector. This result is also coherent with the EU trend already discussed.

As a consequence of this shift, Italy and Spain have rapidly become (Fig. 7) two large players in the EU's production (82% together with the Netherlands) of palm-based biofuel (Transport&Environment, 2017, 2018). For instance, Spain, the EU leader in the sector, between 2005 and 2013, has hugely increased (approx. + 4000%) the domestic biodiesel production capacity (USDA 2020), which is currently almost only based on palm oil derivatives (El Confidencial 2019). In the case of France, instead palm oil imports destined to the energy sector represented the largest share all over the period. This trend may have been the result of both the broad differences in the French customs taxes regime between palm oil used in food or biodiesel (benefiting from environmental tax advantages during the assessment period) (Reuters 2016; Transport&Environment 2020), and a more determined concern of the French politics, compared to other EU's member states, in halting the imports of embodied deforestation (FERN 2019).

The contribution of the German oleochemical sector—residual within the other European economies—is the largest among targeted countries: this relates to the fact that Germany has the largest cosmetics market in Europe, which in turn "*is the global flagship producer of cosmetic products*" (Cosmetics Europe 2019).

Overall, the different and sometimes unstable trends (such as in the case of Germany since 2009) can be driven by different factors, including policies to orient household and enterprises consumption, and fluctuations in the stock and prices of potential alternatives such as soybeans and rapeseed oil. Alternative vegetable and animal fats—like butter, olive oil, and sunflower oil—might also have played a role in the food sector in Italy, France, and Spain. For instance, between 2000 and 2020 France and Spain have been respectively the fifth and sixth global producers of sunflower oil (Faostat 2023).

Concerning the third and the fourth research questions objective and the quantification of the embodied impacts, our results demonstrate how, over the last two decades, the environmental pressure by the major European economies on the targeted tropical producing countries has increased. Indeed, the overall expansion of agricultural lands—i.e. the land footprint—(Fig. 9) needed to serve the growing EU palm oil consumption has driven an increase in the related embodied environmental impacts. In 2000, the four importing countries displaced on average less than 0.08 Mha within the three producing countries, whereas, since 2008, this figure has more than doubled, being on average around 0.32 Mha between 2014 and 2016 (Fig. 9).

When comparing the mean annual domestic area harvested for oil crops production between 2000 and 2020 in each of the four countries (Faostat 2023) with the yearly average land footprint (Table 3) for oil palm consumption in the same period, it is possible to estimate the share of domestic croplands that would have been necessary to attain the same consumption patterns. For instance, on average annually, to fulfil the reported consumption trends, without palm oil imports and considering yield effects,[9] France would have used 27% more of its domestic agricultural lands specifically devoted to oil crops production, Germany 83% more, Italy 124% more, and Spain 34% more.

Concerning the embodied deforestation assessment, we estimated three measures characterized by considerable differences in the assumptions describing the link between palm oil production and deforestation trends. Therefore, given these already discussed conceptual and methodological divergences (paragraph 3.3.2), the results of the concession-level approach cannot be compared with those of the historical and the rapid perspectives. Nevertheless, the three perspectives, all together, can draw a broader picture in the assessment of the deforestation incorporated in palm oil's apparent consumption.

Indeed, the first approach focuses on specific deforestation trends registered within a representative sample of large-scale operators in the palm oil industry across the three producing countries. The underlying statistics, provided by several remote sensing analysis tools and techniques, represented the "finest resolution" for this study to link final consumption to annual LUC activities on the ground. In addition, the second and third approaches were chosen to tell a still relevant but completely different story on the European impact of palm oil consumption. On the one hand, the historical perspective emphasizes how the changes in European consumption and trade patterns have been contributing significantly over time to shaping the global land surface. To this purpose, for instance, the historical share of deforestation attributes the deforestation's one-time event over future agricultural production activities and multiple harvesting cycles by allocating all the past forest loss registered within a current unit of agricultural land, without considering a so-called fixed "amortization period" (Persson et al. 2014, Henders et al. 2015; Pendrill et al., 2019a, b). On the other hand, the rapid-conversion approach attributes the hectares of forest loss, which occurred in a given year and within a specific land area, only over the next five years of agricultural production and trade.

Overall, despite the significant differences in the methods applied and the period considered, our estimates, reported in Tables 5, 6, and 7, can be compared with those of two ground breaking studies concerning the impact of the EU's consumption of FRCs on tropical deforestation.

Cuypers et al. (2013) estimated respectively 0.9Mha and 47kha/yr of total and mean annual embodied deforestation within the EU net imports of palm oil and its derivatives between 1990 and 2008. Whereas, in this study the average, among the four importing countries, of the total and the mean values of embodied deforestation between the second and the third approaches (Table 5) are respectively 0,68Mha and 32Kha/yr, namely 75% and 68% of Cuypers' estimates.

Hence, given that the four EU targeted countries currently represent respectively around 57% and 66% of the EU's population and GDP, and that after 2008 an increase both in the EU palm oil imports and population have been registered, our results can be considered in line with the first EU's study on embodied deforestation in the palm oil apparent consumption.

[9] For each European country we considered the differences in yield (Meijaard et al. 2018) between the main domestic oil crop and palm oil.

According to Pendrill et al. (2022b), between 2005 and 2018, the mean annual deforestation risk within Indonesia, Malaysia, and Papua New Guinea, caused by the net imports of palm oil and its derivatives by Italy, Germany, France, and Spain has been respectively 8651 ha, 9935 ha, 2985 ha, and 7719 ha. Moreover, by dividing the total embodied deforestation risk by the mean population during the period for each importing country, the estimates of the per-capita embodied deforestation based on Pendrill et al. (2022b) correspond to 1.4m^2 for Italy, 0.5m^2 for France, 1.2 m^2 for Germany, and 1.7 m^2 for Spain. All of these values fall within our rapid and historical mean annual and mean annual per-capita ranges of values of embodied deforestation per country of import (Tables 6 and 7).

Main limitations and possible ways forward

This study represents an attempt to provide a straightforward methodology to estimate the role of EU consumption of South-East Asian palm oil and its impacts in terms of deforestation and contribution to the climate change in the last two decades. Despite our efforts, the study includes some limitations, e.g., in terms of data accuracy. Our data, indeed, refer mainly to national statistics and have been subject to rounding, averaging, and simplifications. Furthermore, as in the case of the annual approach, available data are not entirely consistent in temporal and spatial perspectives. Therefore, a general increase in data accuracy would improve our estimates.

Overall, a key improvement would consist of the use of data and statistics at the subnational level, for instance regarding yields, mill's production capacity, and deforestation activities that occurred in different sub-national provinces and/or production districts as shown for instance for similar studies with other commodities (Godar et al. 2015, 2016; Croft et al. 2018; Ermgassen et al. 2020; Escobar et al. 2020). This information, while providing a higher level of granularity, could better link the consumption in importing countries to specific palm oil production areas (e.g., sub-national region, municipality, or even single concession), as well as opening the doors to the tracing back of the link between consumption and associated environmental impacts. Based on more robust quantitative data on a local scale, we could define a more solid research ground for an in-depth estimation of the socio-ecological impacts embedded in consumption, having the chance to focus on the main actors involved within the palm oil supply chains. A concrete potential improvement for this kind of analysis is linking imported quantities in volume to specific production districts and even to processing companies and traders characterized by different environmental and socioeconomic performances (Godar et al. 2016). Hence, a desirable way forward to better associate environmental impacts with the production, trade, and consumption of FRCs might be represented by the increasing availability of so-called "middle-ground analysis" (Godar et al. 2015, 2016), which combine the functionality of top-down approaches with the flexibility and granularity of bottom-up or local scale approaches (Corrado et al. 2020).

Conclusions

The increasing qualitative and quantitative reduction of natural capital determines the emergence of trade-offs between economic growth and environmental degradation (Foley et al. 2005, 2011). LUC processes linked to the production of agro-commodities affect natural ecosystems, leading to both short-term—e.g. the supply of raw materials and income generation—and medium to long-term socioeconomic and environmental impacts—e.g. deforestation and climate change. All these impacts ultimately have direct or indirect effects on human well-being (DeFries et al. 2004). Therefore, policy measures to address these issues should be supported by qualitative and quantitative assessments of the socioeconomic and environmental consequences stemming from LUC processes (DeFryes et al. 2004).

In this context, the international trade of agricultural commodities is acting globally as an indirect driver of natural ecosystem degradation. Consequently, this study aimed to provide up-to-date results on the EU's embodied deforestation, considering a handful of specific bilateral trade flows in the palm oil sector. Two novelties of this work relied on the differentiated analysis by sector of final consumption and the attempt to overcome the issue of intermediate trade countries in modelling environmental footprints embodied in trade. The latter represents, for instance, the main limitation of Cuypers et al. (2013)'s quantitative results.

Firstly, through a physical accounting model, we detected direct and indirect trade networks, highlighting the differences among the four targeted European importing countries in trade partners and consumption trends of oil palm fruits equivalents.

Different trade profiles have emerged from the network analysis of trade among the four importing countries. Italy and Spain showed a major direct trade link with producing countries, while France and Germany had significant trade connections with non-producing countries (i.e. intermediate trade partners). When the trade network of intermediate trade partners was further assessed, Indonesia became the main trade partner, Malaysia the second and PNG the third for all the EU countries.

The overall increase in the consumption of palm oil and its co-products over years was mainly determined by the share of imports explicitly driven by the demand of the EU's energy sector (i.e. biofuels). Several socioeconomic and political endogenous—e.g. policies to orient household and enterprises consumption—and exogenous—e.g. fluctuations in the global market of the stock and prices of potential alternatives—variables might have had a role on the different and sometimes unstable trends in the allocation among the sectors.

The growing demand for palm oil as a feedstock for energy production corresponded to increased environmental embodied impacts. For instance, between 2000 and 2020, the total land footprint related to palm oil consumption has increased four-fold (an average of 0.8 Mha/yr).

Building on this, pivotal policy implications can arise. The transition to renewable resources to produce "clean energy" needs to account for the environmental impacts of LUC activities within countries harvesting primary energy crops. On this issue, the so-called concept of "ecosystem carbon payback time", namely the length of time needed by the positive effect of producing energy without burning fossil fuel to offset the carbon footprint embodied in the production of one ton of energy crop (Gibbs et al. 2008), has become an essential component in order to compare the environmental consequences of a bio-economy against a low carbon economy. For instance, a study of the EC revealed the risk of increasing emissions when fossil diesel is replaced with biodiesels from virgin vegetable oil, and LUC emissions are taken into account (Transport&Environment, 2016a, 2016b). Therefore, our results in terms of per-capita embodied deforestation and per-capita CO_2 emissions (Table 7) could be interpreted as a way to assess and compare the environmental impacts of different energy commodities—per unit of energy density[10]—and alternative socio-economic pathways to address the future EU's per-capita energy consumption. Furthermore, future environmental trade-offs analysis within the EU's energy sector might significantly change following the put in force of a law removing palm oil from a list of permitted biofuels from January 2020 and eliminating related tax exemptions (Reuters 2022).

As a result of the embodied deforestation assessment, over the period considered, according to the second and the third approaches, between 5–78 m^2 of deforestation and 28–445 kg CO_2 emissions associated with LUC activities have been incorporated in the per-capita consumption of palm oil and its co-products in the leading European economies. Moreover, taking into account the first approach (i.e. the concession-level) and the allocation by sector, we concluded that the German food sector is the one that embodied the larger deforestation footprint, followed by the Italian and the Spanish energy sectors.

Overall, results are similar to previous leading studies on embodied deforestation and CO_2 emissions in the EU's palm oil consumption.

Moreover, since the global market of substitute goods (i.e. soybeans, rapeseed, and sunflower) is strongly interconnected, our results can also be functional when comparing the EU environmental footprint of the consumption of the main alternatives of palm oil. In this respect, the unilateral ban or a substantial reduction in the EU palm oil imports could merely determine the displacement of the environmental impacts elsewhere (e.g. even more agricultural land footprint in Europe). In this context, for instance, the identification of a sustainable basket of products, having the potential to meet the EU demand and at the same time to minimize the embodied environmental footprint would represent a suitable tool for policymakers to measure the sustainability trade-offs between alternative consumption choices. This kind of analysis should be based on quantifying and comparing several impact indicators (e.g., deforestation and carbon footprints), which would allow for a comprehensive and informative comparison between the socioeconomic and environmental implications arising from specific LUC processes at different spatial and temporal scales, as well as considering their implications in terms of well-being changes for different stakeholders groups.

Hence, the future EU policy agenda, aimed to halt deforestation by creating "deforestation-free" global value chains in the context of a long-term project for the overall reduction of the environmental impacts outsourced from outside the EU, should be further developed considering those trade-off analyses.

Regarding the need to perform a stakeholder-focused economic analysis, it is worth considering that countries qualifying as net exporters of natural capital, strongly depend, both socially and economically, on the international markets of Forest and Ecosystem

[10] It measures the release of energy (Mj) given a unit of mass (kg) of a specific fuel/biofuel.

Risk Commodities (FERCs). An EU rebalancing of consumption patterns and a subsequent reduction of the environmental footprints embodied in global trade must therefore be complemented by targeted supply-side measures within exporting countries.

Abbreviations

LUC	Land-use change
FRC	Forest risk commodity
EU	European Union
GDP	Gross domestic product
GHGs	Green house gases
AFOLU	Agriculture, forestry and other land use
FLEGT	Forest Law Enforcement, Governance and Trade
EC	European Commission
EUTR	European Union Timber Regulation
RED	Renewable energy directive
LF	Land footprint
FAO	Food and Agriculture Organization
LU	Land-use
CPO	Crude palm oil
CPKO	Crude palm kernel oil
RSPO	Round table for sustainable palm oil
ROW	Rest of the world
ITC	International Trade Center
ADI	Annual deforestation intensity
AGB	Above ground biomass
FERC	Forest and ecosystem risk commodities

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40100-023-00268-5.

Additional file 1. Further details on: Trade data mining and cleaning (Step 1). Consumption by economic sector and exporters ranking (Step 2). Land Footprint estimation (Step 3). Trade network analysis (Step 4). Embodied deforestation (Step 5). Per-capita deforestation footprint and per-capita embodied carbon dioxide emissions (Step 6).

Acknowledgements

This work was realised with the collaboration of the European Commission Joint Research Centre under the Collaborative Doctoral Partnership Agreement No 35456. This study was supported by the Directorate-General for Environment of the European Commission (DG ENV) through the Dev-ForObs Administrative Arrangement ("EU Observatory on deforestation, forest degradation, changes in the world's forest cover, and associated drivers").

Author contributions

GB is the main author. GB defined the research questions, made the literature review, selected the relevant databases, gathered and analysed the data, developed the land footprint model, and wrote the paper. MM[1] made substantial contribution in designing, developing and revising the paper. DP revised the paper critically mostly regarding the EU policy related aspects and the overall data quality. MM[2] made substantial contribution in developing the land footprint model and revising the paper. PR made substantial contribution regarding trade data gathering and manipulation within the Python environment. All the authors read and approved the final manuscript.

Funding

The research funding was provided by the Joint Research Center (JRC) of the European Commission, Sustainable Resources Directorate, and by the Department of Land Environment, Agriculture and Forestry (TESAF) of the University of Padova.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 21 November 2022 Revised: 21 March 2023 Accepted: 14 July 2023
Published online: 14 September 2023

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