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Stimulating environmental degradation: A global study of resource use in cocoa, coffee, tea and tobacco supply chains

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ABSTRACT

Stimulants play a central role in modern human society. Consumption of stimulants transcends culture, demography, and income group. As cash crops, stimulants (such as cocoa, coffee, tea and tobacco) also act as a source of economic security for producers in low-income countries. However, satisfying the demand for stimulants entails a potentially large environmental cost. This burden demands careful attention given the potentially negative impact of stimulant production on local food security. To date, stimulants have been peripheral to the research and policy agenda on sustainable food systems. We undertake the first global assessment of water, land and fertiliser use associated with cocoa, coffee, tea and tobacco production, consumption and trade, across 254 countries, between 2002 and 2017. Globally, resource use associated with these stimulants (except for tobacco) grew substantially over this period. In 2017, the stimulant economy required i) land use equivalent to the total land area of Italy; ii) green and blue water equivalent to the food sectors of Brazil and Portugal, respectively; and iii) fertiliser use equivalent to India's total fertiliser demand in the same year. We show that the main centres of resource use and demand associated with stimulants implicate a few major countries, presenting management opportunities through supply chain screening of resource-intensive production sources and targeted demand-side policies. Differences between stimulant's resource use also highlights the potential for substitution of consumption to reduce environmental pressures across this system.

1. Introduction

Measures that address the degradation and over-exploitation of natural resources are urgently needed (UNDP, 2014). However, the extraction and use of natural resources are highly interconnected, spatially and sectorally, within a complex web of global interactions and feedbacks. The provision of goods and services relies on dense networks of producers whose activities are linked across multiple countries and sectors (Liu et al., 2015). As such, the link between consumption decisions and their impact on natural resources are often remote. Agricultural commodity supply chains represent an important system of study within this context (Rockström et al., 2020). The global agri-commodity system connects billions of consumers, millions of farmers, and a small, but opaque, group of trans-national businesses who command control of agricultural production and its vast natural resource burden (Henson and Humphrey, 2010; Porfirio et al., 2018).

Recent scholarship has highlighted the increasing importance of agricultural commodity trade as a source of water depletion (Dalin et al., 2017; Lenzen et al., 2013; D'Odorico et al., 2019; Caro et al., 2021), land displacement (Bruckner et al., 2015; Chen and Han, 2015; Godar et al., 2015; Osei-Owusu et al., 2019), and environmental pollution (Wiedmann and Lenzen, 2018; Li et al., 2019; Bruckner et al., 2019). Specific agricultural products have received significant attention, including soy (Taherzadeh and Caro, 2019; Caro et al., 2018; Heron et al., 2018; Croft et al., 2018) wheat (Zhang et al., 2017; Hanasaki et al., 2010; Linquist et al., 2012), rice (You et al., 2011; Tuong and Bouman, 2009; Haefele et al., 2014; Sporchia et al., 2021b) and livestock products (Poore and Nemecek, 2018; Bruckner et al., 2019; Sporchia et al., 2021a). A growing interest in the environmental burden of diets (Batlle-Bayer et al., 2020; Bruno et al., 2019) has reinforced this selective focus on staple food products (Laroche et al., 2020; Poore and Nemecek, 2018). Although widely traded and consumed, stimulants, such as tea, coffee, cocoa and tobacco have received considerably less attention in resource footprinting of agricultural commodities and diets. Extending resource footprinting and management to cover stimulants is warranted on several fronts. Stimulants are more resource intensive than many other common agricultural products (Chapagain and Hoekstra, 2007; Yang and Cui, 2014; Pfister and Bayer, 2014); they have a greater potential to undermine food security in producing regions (Kuma et al., 2019; Bymolt et al., 2018; Bitama et al., 2020; Appau et al., 2019); and their cultivation is highly concentrated, presenting major opportunities, but also risks, to their responsible management (Li and Tang, 2018; Voora et al., 2019; Moat et al., 2017).

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Several insights have emerged from the limited study of resource use within the stimulant economy. First, demand for stimulants has been found to account for a large share of non-territorial resource use driven by mostly wealthy nations (Würtenberger et al., 2006; Chapagain and Hoekstra, 2007; Gerbens-Leenes and Nonhebel, 2005; van Oel et al., 2009a). Second, unsustainable levels of resource use have been observed in stimulant production systems, encouraging groundwater depletion (Allan, 2011; Chapagain and Hoekstra, 2008; Mekonnen and Hoekstra, 2011), monoculture (Carrasco et al., 2017), and soil pollution from fertiliser application (Nesme et al., 2016). Third, vastly different levels of stimulant consumption between countries and continents implicate a few major consumption centres in the resource burden of stimulants and their responsible sourcing. Although instructive, these early studies of resource use driven by stimulants have been limited by a focus on single producing or consuming nations, global trends, and limited environmental impact areas. This scope has prevented a meaningful comparison between specific commodities and consumer responsible for their impacts.

To support a deeper understanding of the resource burden driven by the stimulant economy, this study evaluates the pathways of water, land and fertiliser use embodied in tea, coffee, cocoa and tobacco supply chains, covering 254 countries, from 2002 to 2017. In addition to constructing a database linked to these commodities' resource use, this study attempts to evaluate their relationship with producer prices to understand the resource-revenue trade-offs and co-benefits involved in stimulant production.

This study begins, in Section 2, by outlining the methodological procedures, analytical framework and data required to calculate resource use linked to stimulant production, consumption and trade. Section 3 presents the results of this analysis from the perspective of producers (Section 3.1), consumers (Section 3.2), and in relation to producer resource and economic efficiency (Section 3.3). Lastly, Section 4 discusses the limitations of this study and its implications for sustainable management of stimulants within the context of water, land and fertiliser use.

Our findings reveal large disparities between (i) the water, land and fertiliser footprint of tea, coffee, cocoa and tobacco; (ii) the scale and geography of their demand; and (iii) the prices producers receive for different levels of resource input.

2. Methods and data

Cash crops evade straightforward definition due to the commodified nature of agricultural production. However, Achterbosch et al. (2014) distinguish two main qualities of agricultural products which invite this categorisation. First, cash crops include food or non-food agricultural products and are principally grown as a source of farmer income. Crops produced with a 'marketable surplus' might also be considered cash crops as well. Among the crops studied here, only cocoa is considered as food, since it contains various nutrients, whereas coffee, tea and tobacco are commonly defined as non-food crops (FAO, 2020a). Moreover, these crops are often referred to as "stimulant crops" since they contain alkaloids, which are active elements affecting human physiology (FAO, 2020b). This further classification is relevant due to both the non-essential nature of stimulant crops in achieving food security and their non-trivial environmental impact, identified in this study and elsewhere (Mekonnen and Hoekstra, 2011). Second, cash crops tend to be produced for markets and consumers beyond their country of origin, raising important concerns about the fair distribution of risks (social, economic and environmental) between actors in global supply chains. The crops studied here exemplify the growing significance of cash crops within this context.

Cocoa demand is expected to grow in the future, driven by its existing consumer base (i.e. the United States and Europe) but also emerging economies, whilst its production will remain concentrated in a few developing countries (Voora et al., 2019). Price volatility is the main source of risk affecting cocoa farmers (mostly smallholders) and is compounded by the uneven sharing of profit across the value chain, which has attracted international regulation and standards (Voora et al., 2019). Demand for coffee has also grown dramatically in recent decades and is expected to grow in new and existing markets (Torga and Spers, 2020). However, as for cocoa, price volatility, together with the changing environmental conditions, affect coffee production as well, requiring strong coordination among the actors involved in the value chain to protect farmer livelihoods (Beck et al., 2016). Tea is cultivated in an increasing number of countries, but the bulk of production (and often consumption) remains highly concentrated geographically (FAO, 2020b). Climate change is also likely to reduce the cultivation area and associated yields of tea (Ahmed et al., 2018), potentially encouraging more intensive forms of tea production and associated resource use in order to meet increased future demandcompared with tot. Smallholders represent the largest proportion of tea farmers. However, as with the other cash crops within this study, a few companies control most of the trade within a market system based on auctions with anonymous transactions, often at expense of farmer incomes (FAO, 2018). Child and forced labour, poor working conditions and low wages are symptomatic of these inequalities (Panwar, 2017; Baro, 2016). Tobacco consumption is growing, driven by consumption in middle- and low-income countries, whereas its production is more widely spread when compared with the other three crops analysed (WHO, 2020; FAO, 2020b). Five multinational companies control most of the global tobacco market, which is expected to shift from regions where policies are becoming increasingly restrictive (e.g. European Union), to regions with lax environmental and social regulations, such as Africa and Asia (Euromonitor International, 2019; Yerramilli, 2013).

2.1. Calculating resource use linked to stimulants

Resource use associated with crop production varies within and between different commodity markets due to different climate, environmental conditions and farming practices. Within this study we attempt to capture these differences in relation to tea, coffee, cocoa and tobacco production. However, resource requirements data linked to such crops are typically fragmented and limited in scope, demanding the use of global averages and modelled estimations. Within this section we summarise the data, methods and assumptions associated with calculating water use (Section 2.1.1), land use (Section 2.1.2) and fertiliser use (Section 2.1.3) linked to the commodities studied.

2.1.1. Water use

The water requirements of crops analysed within this study were sourced from Mekonnen and Hoekstra (2011) and compiled based on the methodology developed in Hoekstra et al. (2011). However, instead of assuming a constant and globally uniform crop water intensity, that fails to capture the temporal and spatial variability of crop water efficiency, we estimated country-specific crop water intensity values on an annual basis, following Sporchia et al. (2021b). For each producing country, year and crop, we calculate the Specific Water Demand (*SWD*) (the volume of water required to obtain a quantity of a given commodity, expressed in m^3T^{-1}) as the ratio between the Crop Water Requirement (*CWR*) (namely, the volume of water used per cultivated area, expressed in m^3ha^{-1}), and the yield (*Y*), expressed in Tha^{-1}, as follows:

$$SWD_{c,n,y} = \frac{CWR_{c,n}}{Y_{c,n,y}} \quad (1)$$

where *SWD* indicates the specific water demand in country *n* in the year *y* for crop *c*, *CWR* the water requirement of crop *c* in country *n*, and *Y* refers to the yield of crop *c* in country *n* in the year *y*. For the majority of the countries analysed, *CWR* was sourced from Mekonnen and Hoekstra (2011). For the few countries where such information was missing, we used global averages provided in the same study. The underlying data, reported in full in the *supplementary material* ('*Definition and data Sources - Table S1*'), distinguishes the green and blue water use associated with each crop.

2.1.2. Land use

Following the approach used in previous studies (Taherzadeh and Caro, 2019; Kastner et al., 2014), land use associated with each of the crops analysed within this study is based on data from FAO (2020b). These data are collected and compiled by the FAO from national authorities through annual questionnaires with gaps in reporting filled by modelled estimates. For each producing country, year and crop, we derived the land use intensity from the reciprocal of the yield, expressed as haT^{-1}.

2.1.3. Fertiliser use

Fertiliser input was estimated following the approach of previous studies (MacDonald et al., 2012; de Ruiter et al., 2016). However, in contrast to data on water or land use, data on crop fertiliser use is less widely available which prevented reliance on a single, central database. Whilst Lassaletta et al. (2016) provides an overview of global agricultural nitrogen inputs, the resolution of this study does not match the country-level specificity of this study's analysis and relies on estimated nitrogen application rates instead of reported values. Moreover, no study provides phosphorous and potassium input data at the scope of our analysis. Accordingly, we compiled aggregate fertiliser use data from IFA and IPI (2002), FAO (2006), and Gockowski and Sonwa (2011). For each producing country, year and crop, we used the fertiliser application rate (*AR*) data, expressed in tonnes of fertiliser use per hectare (Tha^{-1}). Since data pertaining to the application of single nutrients (e.g. nitrogen, phosphorous, and potassium) were only available for few countries, aggregate fertiliser application data, expressed in the form of NPK (final mix of Nitrogen, Phosphorous, and Potassium applied), which are more widely available, were used. Where fertiliser application rates were not available we used available regional averages.

We estimate the annual fertiliser application rate for each crop using a production-weighted share of each country's total fertiliser output, as follows:

$$FUS_{c,n} = \frac{FU_{c,n,y}}{TFU_{n,y}} \tag{2}$$

where *FUS* indicates the fertiliser use share for the crop *c* in the country *n* and *FU* indicates the fertiliser use for the crop *c* in country *n*. For both *FUS* and *FU,y* refers to the year of the latest available data, which varies by country (IFA and IPI, 2002; FAO, 2006; Gockowski and Sonwa, 2011) (see details in supplementary material,'*Definitions_and_Data_sources.ods - Tables S2-S5*'). *TFU* indicates the total fertiliser use of the country *n* in the year t. For each crop *c,* and for each country *n*, the fertiliser use (*FU*) was estimated as the product of the share (*FUS*) and the total fertiliser use (*TFU*) for the same year, as follows:

$$FU_{c,n,y} = FUS_{c,n} \times TFU_{n,y} \tag{3}$$

where a country's fertiliser application rate was not reported, or no regional average was available, we assigned a value of zero. However, the combination of country-specific and average fertiliser data covered a number of countries responsible for more than 80% of global production (see supplementary material, '*Defi.nitions_and_Data_sources.ods - Table S6*'). Only for tea, where fertiliser use covered around 65% of the world production, did we apply a fixed global average application rate to countries lacking data.

2.2. Linking production impacts to trade

For each crop, production and trade data were sourced from FAO, (2020b), capturing all 254 countries included in FAOSTAT database. Since FAO trade data do not distinguish re-exported commodities, to avoid double counting commodity flows and associated resource use, we applied the approach of Kastner et al. (2014) to ensure the correct allocation of commodity flows to their country of origin. This method is based on the assumption that only producers of a given commodity can export it and that export flows cannot exceed what is domestically produced (if any) and imported (if any). This condition aims to correctly identify and preserve a commodities origin throughout trade-related environmental flow analysis. By tracking commodity re-export flows it is possible to trace a commodity from its origin of production to its location of final import. Although this allocation approach offers superior coverage of commodity flows upstream supply chains when compared with using bilateral flow data alone, it does not necessarily capture their location of final consumption, as in Multi-Regional Input-Output Analysis (MRIOA). Hence, the countries identified as 'consumers' of cocoa, coffee, tea and tobacco, reported in Section 3.2, might be intermediary actors in longer, more complex supply chains, and involved simply in the processing and further export of these commodities. The lack of processing data prevented the full traceability of the commodity supply chains studied.

The treatment of commodity flows was applied to all countries and commodities within this study, by linking bilateral trade flow data with domestic production information. This avoided a potentially large misallocation of commodity flows and associated miscalculation of resource use of and responsibility for the commodities studied (Fig. 1).

In 2017, we estimate the correct allocation of commodity flows within our analysis results in an avoided misallocation of trade flows by 16% for cocoa, 9% for coffee, 15% for tea, and 24% for tobacco. The importance of this allocation is also perceptible at the country level. In 2017, Poland produced 32,493T, imported 126,881T, and exported 30,031T of tobacco, according to FAO trade and production data. After applying the aforementioned data treatment, we estimate Poland had a net import of 102,664T, a net export of 5841T of tobacco, a 20% lower import volume, and an export volume one-fifth of that calculated using bilateral data alone. Data were also amended to exclude countries with negative apparent consumption due to inconsistencies between production and trade accounts within the FAOSTAT database. These procedures are summarised in Fig. 1 using a simplified example. Production and trade data for the crops studied refer to the specific commodity classifications in the FAOSTAT database (see supplementary material, '*Definitions_and_Data_sources.ods - Table S7*').

2.2.1. Estimation of resource footprint

The use of resources required to produce crops in producing countries is driven by both domestic and non-domestic demand. To assign responsibility for crop production and its associated resource we follow a consumption-based accounting approach (see Kanemoto et al. (2012)), allocating resource use to the country where an item is imported. The resource footprint (*RF*) of each nation *n* is equal to the sum of the resource use associated with domestic production for domestic consumption (if any) and the resource use embodied in imports (hereafter 'Virtual Resource Imports'), minus the resource use embodied in exports, as follows:

$$RF_{r,n,c,y} = \overbrace{RI_{r,n,c,y}\cdot\left[P_{n,c,y}.D_{n,c,y}\right]}^{\text{Domestic RF}} + \overbrace{RI_{r,t,c,y}\cdot\sum_{n\neq t}\left[P_{t,c,y}.D_{t,c,y}\right]}^{\text{Virtual Resource Imports}} \tag{4}$$

where $RF_{r,\ n,\ c,\ y}$ refers to the resource footprint of a given country, *n*, for a given resource *r* (i.e. water, land or fertiliser) and crop *c* (i.e. tea, coffee, cocoa and tobacco), in a given year, *y*; $RI_{r,\ n,\ c,\ y}$ and $RI_{r,\ t,\ c,\ y}$ refer to the resource intensity of a crop, as described in Section 2.1, sourced domestically (*n*) or from a trading partner (*t*); $P_{n,\ c,\ y}$ and $P_{t,\ c,\ y}$ refer to the overall production volumes of crops; and, $D_{n,\ c,\ y}$ refers to domestic demand, whilst $D_{t,\ c,\ y}$ refers to the relative demand for their production from country *t*. Production and trade data were extracted form FAO (2020b). According to eq. (4), a crop exported from a certain country must be grown in this country and not in another country from which it was imported for further export. The application of Kastner et al. (2014) treatment to trade and production data ensures the consistency of this assumption.

2.2.2. Indexing operation

The multi-dimensional nature of this analysis, covering multiple resource systems and countries, renders the visualisation of data arising

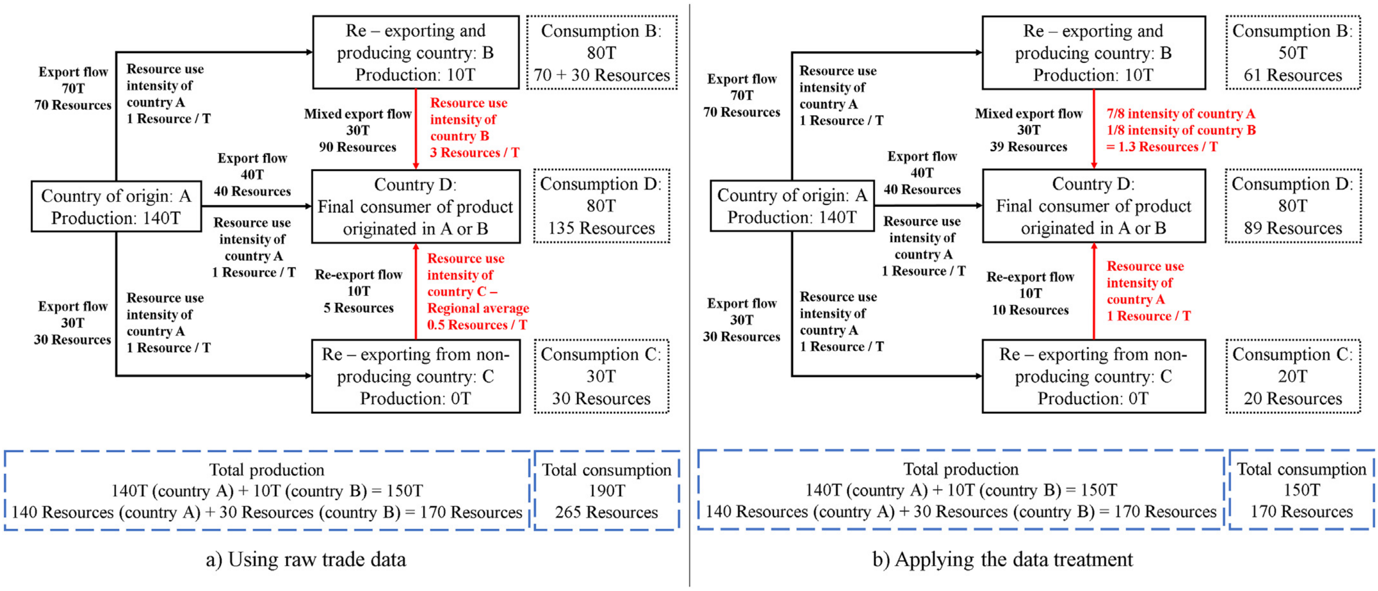

Fig. 1. Schematic representation of the method used to allocate the commodities to final importers. a) Using raw trade data can result in double counting re-export flows and an incorrect allocation of trade flows their estimated resource intensities. This accounting error results in an inconsistency between production-based and consumption-based resource footprints for a given system. b) By applying the data treatment approach proposed by Kastner et al. (2014) we obtain net trade flows, ensuring the correct accounting of all production and trade data and the attribution of resource intensities, ensuring consistency between production and consumption resource use data. Numbers refer to a hypothetical example involving four countries. Country A and B are the sources of production, whereas countries C and D have no production. In *scenario a* trade data includes flows from country B and C to country D and the resource burden of these flows is calculated using the resource intensities of production in country B and country C for the respective flows. However, the calculation does not distinguish the production source(s) underpinning these trade flows and their associated resource intensities. As a result, the trade flow from country B to country D assumes production and resource use only occurs in country B, instead of distinguishing the production and resource share from country A, resulting in an overestimation of the resource burden of this trade flow. Whilst the trade flow from country C to country D assumes production and resource use occurs in country C, despite all production occurring in country A, resulting in the underestimation of the resource burden of this trade flow. In *scenario b* re-export flows are adjusted in order to reflect the origin of the commodity by applying the approach developed by Kastner et al. (2014). Accordingly, the trade flow from B to D is assigned an intensity proportional to the commodity volume imported and produced by country B. Whilst the trade flow from C to D reflects the origin of the product and is assigned the intensity of country A. Consequently, the resource use related to consumption is consistent with the resource use linked to production (150T of commodity production and 170 resources).

from our analysis complex. To overcome this, we express the country-scale data using a normalised indexing operation. The indexing is compiled as follows in eq. (5)

$$I_{r,n,y} = \frac{RF_{r,n,c,y}}{\sum_{n} RF_{r,n,c,y} \cdot \sum_{r} RF_{r,M,c,y}} \qquad (5)$$

where $RF_{r,\,n,\,c,\,y}$ refers to eq. (4) and $RF_{r,\,M,\,c,\,y}$ refers to the country (M) with the highest overall resource footprint for crop *c* in year *y*.

3. Results

3.1. Dynamics and trends of stimulant crops production and related footprint

The consumption of stimulant crops in 2017 required land equivalent to the total land area of Italy (UNSTATS, 2020), half the global land required for barley production (Mekonnen and Hoekstra, 2011), or the total land area under rice cultivation in China (FAO, 2020b). The green water demand from stimulant production was similar to the overall water footprint of the Russian and Brazilian food sectors, whilst the blue water footprint of stimulants was similar to the overall water footprint of the Portuguese food sector (Taherzadeh, 2020a). Meanwhile, the quantity of fertiliser used for cultivating these stimulant crops in 2017 was similar to the total fertiliser used in India (FAO, 2020b) and exceeded the total fertiliser used for global oil palm cultivation in the same year (IFA and IPNI, 2017). Among the four crops analysed, coffee had the largest production volume, followed by tobacco, tea and cocoa.

As shown in Fig. 2, resource use in producing countries generally followed the same trend but with few exceptions, especially in the case of blue water. For example, land use (10.9 Mha) and green water use (140 Gm^3) for coffee peaked in 2004. Meanwhile, the blue water level kept decreasing from 2002 value (0.89 Gm^3). These changes might be linked to the dramatic decrease of the coffee harvested area that occurred in the Ivory Coast during this period (FAO, 2015).

Among top producers of cocoa and coffee only a few significantly rely on blue water (e.g., Brazil for both cocoa and coffee, and Nigeria for cocoa) (Fig. 2). Instead, blue water use for tea and tobacco production is more common and widespread, and its contribution to the total water use is significantly higher compared with cocoa and coffee (Fig. 2).

From 2002 to 2017, cocoa production increased rapidly across West Africa but decreased in Southeast Asia and South America. Whilst, land, fertiliser and green water use increased in both West Africa and Southeast Asia, but decreased in South America, as shown in Fig. 2). Conversely, blue water use decreased across all major producing regions. Over the same period, coffee production intensified in Southeast Asia whilst green water and land use remained stable due to water use efficiency improvements which offset production expansion in the region (Fig. 2). Meanwhile, Yemen used a significant amount of blue water as well throughout the whole period, a concerning finding when viewed within the context of Yemen's water insecurity (Robins and Fergusson, 2014). China almost doubled its global tea production between 2002 and 2017 and dominated global tobacco production (Fig. 2).

Commodity resource use follows the scale and direction of commodity production and flows. Apart from the large growth of Chinese tea production, for other commodities, only minor producers showed significant production intensification, while most of top producers showed only a modest increase (Fig. 2). Overall, stimulant crops accounted for 253 Gm^3 of green water, covering 4.4% of global green water consumption for crop cultivation (yearly 2000–2009 average according to Schyns et al. (2019)), which is large when considering that they are non-staple food products.

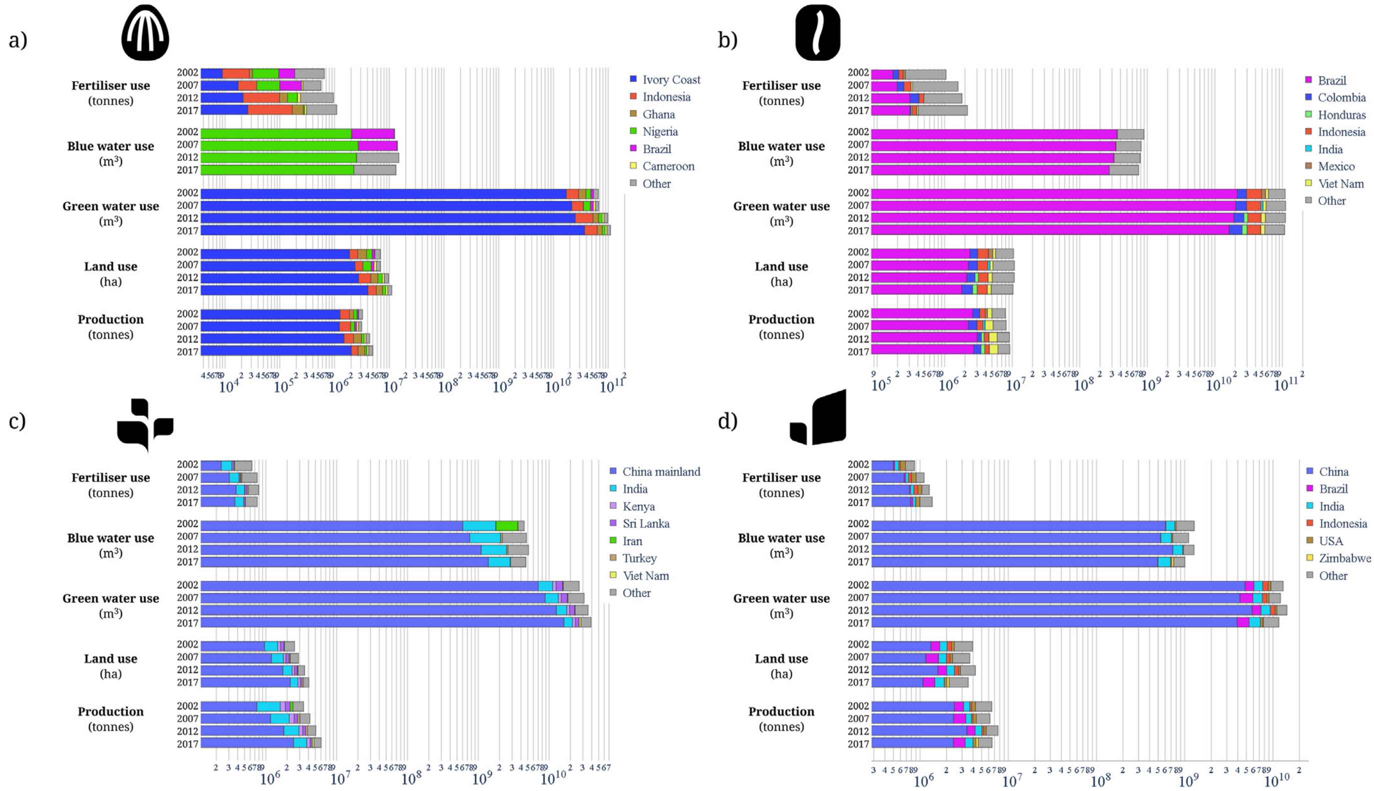

Fig. 2. Global resource footprint and production of a) cocoa b) coffee c) tea d) tobacco at five year intervals between 2002 and 2017. Only the top 5 producers in each year are coloured. Minor producers are included in "Other". See supplementary material, '*Figure_sources.zip* - Fig. 2'.

3.2. Country and consumer responsibility for resource impacts

International trade redistributes responsibility for commodity production and its associated resource use. It is noteworthy that while cocoa production is located in the Global South (e.g. the Ivory Coast, Ghana, Indonesia, Nigeria and Cameroon), European countries account for the largest part of cocoa and coffee consumption. For tea, European countries were second to Asian countries as the main consumers; China alone accounted for around 37% of global tea consumption. China also accounted for the same share of global consumption of tobacco, but other major consumers were evenly spread across the globe. Top consumers of stimulants did not significantly change over time for all commodities. However, the consumption volumes increased. Overall, the responsibility for land, fertiliser and green water use associated with the four analysed commodities mirrored their consumption levels. However, blue water consumption differs significantly. For instance, the largest volumes of blue water use associated with cocoa consumption were found in Brazil, the Netherlands and Germany (Fig. 3). However, in Brazil most of the cocoa consumption was satisfied domestically, where blue water intensity is high. In contrast, blue water use in the Netherlands and Germany linked to cocoa consumption was imposed in Nigeria. Accordingly, the Netherlands and Brazil have the highest per capita blue water use for cocoa consumption (0.05 m^3/capita). Considering coffee, Yemen is a noteworthy case as its consumption accounts for 25% of global blue water use for coffee, despite it not being among the top coffee consumers (Fig. 3). This is the result of Yemen's consumption being satisfied by domestic production which is heavily (60%) reliant on blue water. A similar picture is seen in Iran's domestic tea production and demand. Other top consumers of stimulants also exploit blue water but only marginally (2–5%). Indeed, most top tea consumers' resource use reflects their consumption volumes and not resource inefficiencies associated with their production source. Asian countries accounted for the largest amounts of blue water use for tobacco consumption. However, the highest per capita blue water associated with tobacco is found in Cuba (3.4 m^3/capita), due to high domestic blue water extraction, and Luxembourg (1.2 m^3/capita), owing to its sourcing of tobacco from production sources heavily dependent on blue water. Overall, cocoa showed the highest per capita resource use values for all resources, except for blue water, which was highest for tea. However, in certain countries, the per capita consumption of the commodities studied (e.g. cocoa beans) was significantly higher than the global average. These anomalies might indicate countries acting not merely as consumption centres, but as important hubs for further processing of a commodity within the context of a longer supply chain. This is the case of cocoa for the Netherlands, which is among the countries grinding the largest quantities of cocoa (ICCO, 2019). This is reflected in the high estimated resource use for cocoa consumption in the Netherlands (as shown in Fig. 3), which, however, does not distinguish whether such consumption is driven by Dutch consumption or Dutch demand for cocoa as a raw input in Dutch industry for processing into final products which are consumed elsewhere. Detailed commodity processing data are needed in order to further track this allocation. Moreover, in small coffee producer countries, the existence of high tariffs hampered the export of processed products, creating a relationship of exploitative dependency with consuming countries (Taringana, 2018). Commodity-level MRIO tables or LCA studies will help to capture these flows (see section 4). For other countries, consumption of stimulant crops increased dramatically over the whole period analysed. This is the case of Senegal (from 7T to 6137T of coffee), where the 2008 global financial crisis led to a shift to a less nutrient diet with reduced consumption of dairy (previously imported) in favour of cheaper domestic local coffee (Heltberg et al., 2012), and Angola (from 735T to 14,588T of coffee), where domestic coffee consumption grew following the trend of local production which restarted after decades of abandonment due to war (Bellachew, 2015). Coffee consumption also increased in some European countries, such as Belarus (from 63T to 1334T) and Lithuania (from 86T to 1229T). Tea consumption increased more in minor consuming countries such as Benin, Laos, Albania, Paraguay, Cambodia, Bulgaria and

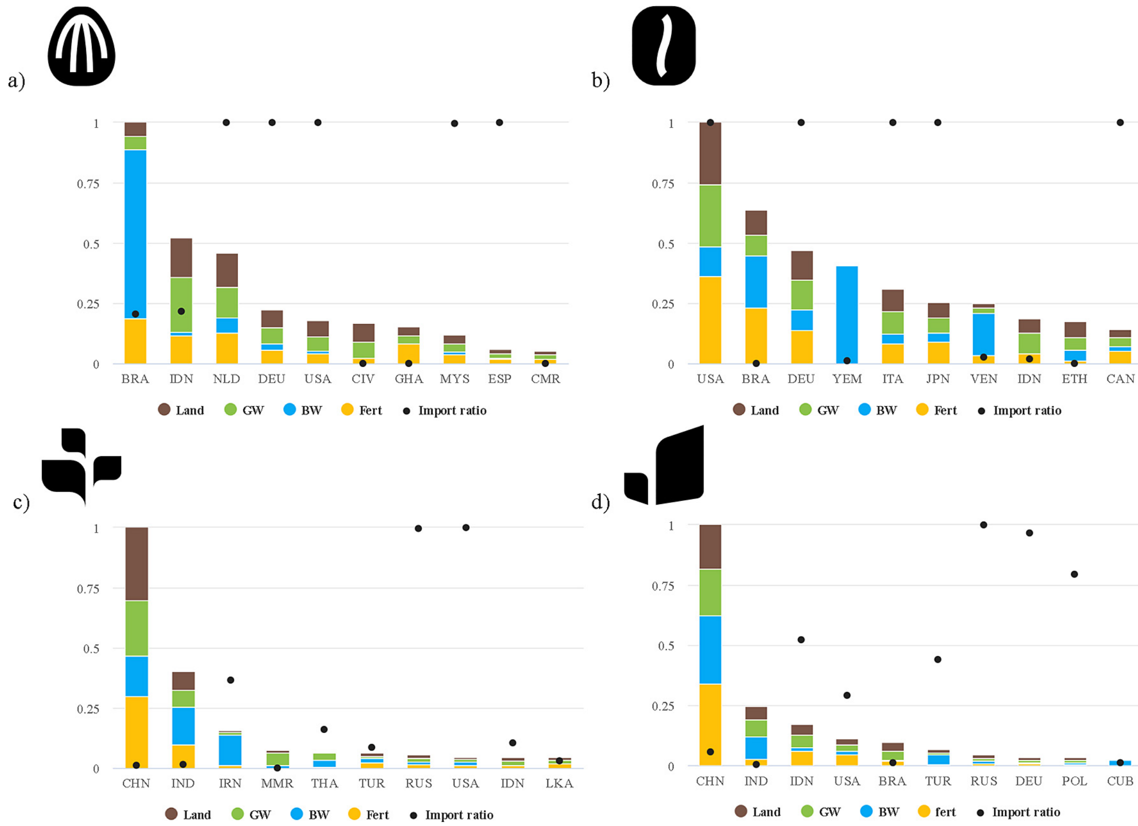

Fig. 3. Top stimulant consumers by indexed total resource use. Using an index it was possible to uniformly present results expressed with various units. For each commodity, country and resource, the consumption value is normalised by dividing it by the global consumption of the related resource for that commodity. The indexing operation is performed by dividing the ratio calculated for each resource by the sum of the ratios of the four resources of the largest consumer. See data in supplementary material, '*Figure_sources.zip* - Fig. 3'. Countries are identified using ISO3 country codes summarised in the supplementary material file *'Definitions_and_Data_sources.ods - List of countries'*.

Gabon, showing a trend of growing consumption. However, it is noteworthy that Chinese consumption increased three-fold while being the largest producer and consumer. Instead, rising consumption rates of tobacco seem to be mostly located in Africa, with Burkina Faso, Namibia, Zimbabwe, Seychelles and Tanzania showing the highest growth rates (by a factor of 5 to 25).

OECD countries covered a large part of the global consumption of cocoa (48%) and coffee (60%), but a low share of tea (12%) and tobacco (19%) consumption. For cocoa (between 40% and 50%) and coffee (between 55% and 70%) they accounted for a significant share of the associated resource use as well, but their share of blue water was lower (14% for cocoa and 30% for coffee). However, the resource use associated with consumption of tea (9%–11%) and tobacco (14%–20%) in OECD countries was less significant.

ASEAN countries accounted for a significantly smaller proportion of global stimulant consumption compared with OECD countries. Only cocoa consumption in ASEAN countries accounted for a large proportion of the global consumption total (22%), whereas the consumption of the other commodities studied was only 8% of the global total. The associated resource use associated with ASEAN stimulant consumption reflected patterns of demand identified within our analysis: 20%–31% for cocoa, 6%–10% for coffee, 4%–20% for tea, and 10%–12% for tobacco. Notably, ASEAN countries were less responsible for blue water use associated with the stimulants studied (3% for cocoa, 0% for coffee and 3% for tobacco) but accounted for 20% of green water use linked to tea consumption.

3.3. Resource and price efficiency of stimulant production

For this analysis we considered only countries whose average production volume was significant, defined as covering at least 1% of the average global production over the period studied. Also, water refers to the aggregate of green and blue water.

From 2002 to 2017, the land use associated with tea cultivation provided the highest economic returns per hectare of land cultivated, an average of 5486 US$ha^{-1}, but a median value of 1707 US$ha^{-1} (Fig. 4). Tobacco, coffee and cocoa followed tea in descending order of economic return per unit of land use. Tobacco and tea showed the highest diversity of economic returns among cultivating countries which also reflected in the discrepancy between median and average values, as shown in Fig. 4.

Tobacco cultivation offered the highest economic return per m^3 of water invested, on average (2.1US$/m^3) with a median value of 1.8US$/m^3. Tea, coffee and cocoa followed tobacco in descending order of economic return per unit of water use (Fig. 4).

Tobacco provided the highest return per unit of fertiliser used compared with the other crops analysed, an average of 43US$/kg of fertiliser and a median of 13US$/kg of fertiliser. Cocoa, coffee and tea followed tobacco with lower average values. As for water, tobacco showed the highest diversity of resource-weighted revenue. However, a high diversity is revealed for all cash crops, as shown in Fig. 4.

3.4. Comparison with previous studies

In 2017, fertiliser consumption linked to stimulant crops accounted for 3% (FAO, 2019). However, it accounted for more than the fertiliser demand in central Europe (10% higher) and west Asia (20% higher) (FAO, 2019). Moreover, coffee alone accounted for more than half of Oceania's fertiliser demand (59%) (FAO, 2019).

Only a small number of previous studies analysed the economic revenue of resource use linked to the production of stimulant crops. Bymolt et al. (2018) found revenue-weighted land use for cocoa of 698$/ha in Ghana

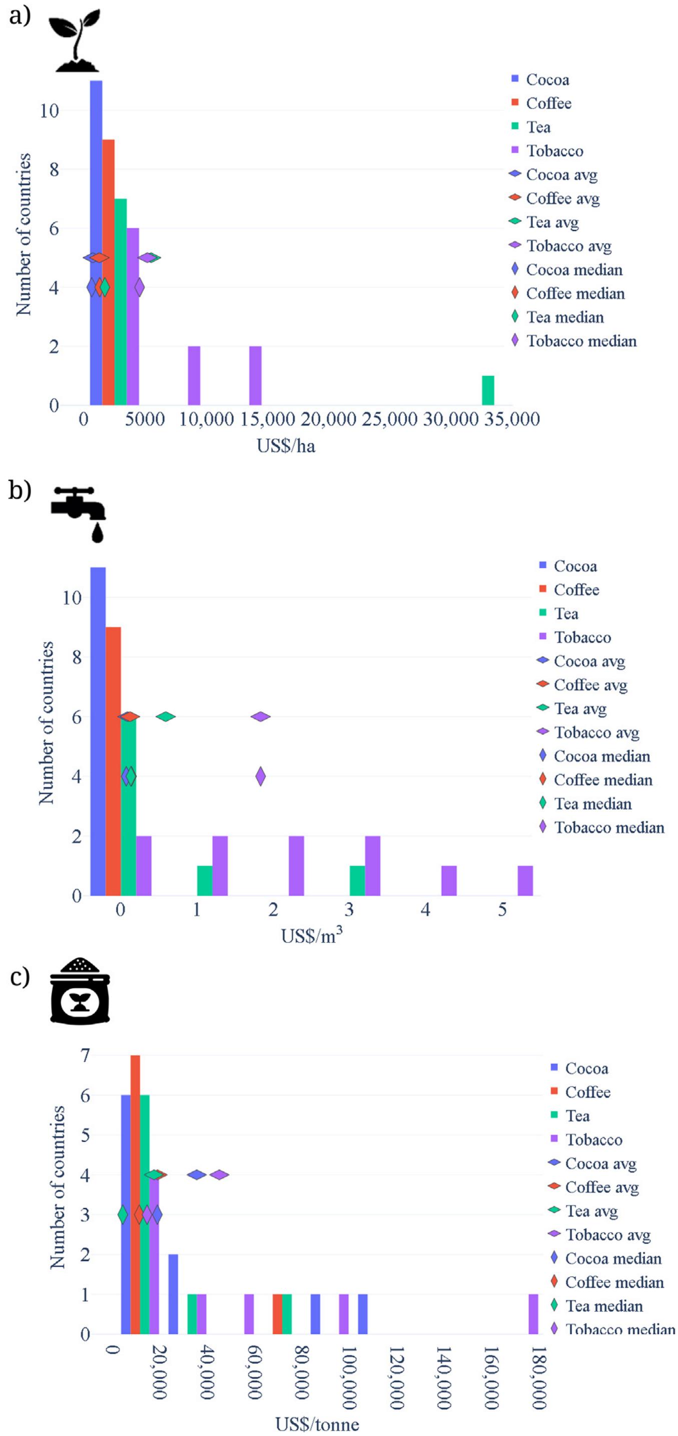

Fig. 4. Price efficiency for a) land b) water c) fertiliser use. Water use refers to the sum of green and blue water use. See data in supplementary material, '*Figure_sources.zip* - Fig. 4'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 579$/ha in the Ivory Coast, which together. Our results are slightly higher (9%) for the Ivory Coast and lower for Ghana (−35%). This difference likely reflects differences in the method, data sources and the period considered. Specialty Coffee Association (2017) found 2415US$/ha as non-weighted average land revenue from coffee among 26 case studies in top coffee producing countries. However, the data used are collected from single farm-scale studies whilst our study relies on national-scale data. Moreover, the temporal scope of this study differs significantly from the analysis presented within our study, preventing a direct comparison. This might explain the difference between our results which estimate a lower land revenue from coffee production (−48%).

An equivalent study by Qiao et al. (2016) for tea found 965US$/ha for organic tea and 278US$/ha for conventional tea in the Wuyuan region in China, and 1061US$/ha for organic tea and 1217US$/ha for the Kandy region in Sri Lanka. The analysis relied on case studies focusing on small-scale farm data from restricted areas within the countries. Moreover, its temporal scope differ significantly from the one of the present study. This might explain the higher results we observed for China (3789US$/ha) and the lower results we observed for Sri Lanka (515US$/ha). Masvongo et al. (2013) found 5120US$/ha for tobacco production in Zimbabwe. However, the study is also only partially representative of Zimbabwe since it refers to an area accounting for 30% of the national production. Moreover, this analysis was based on 2010 and 2011 data and focused only on smallholder tobacco farmers. These differences explain the discrepancy between our result and theirs (−14%) for Zimbabwe.

Mekonnen et al. (2015) analysed the average economic water productivity for Latin America and the Caribbeans during the period 1996–2005, showing that, among the studied crops, vegetables offer the highest economic return per unit of water use ($0.86US\$/m^3$), followed by tobacco. Instead, other stimulants have values generally lower than $0.2US\$/m^3$ (e.g. $0.15US\$/m^3$ for coffee), which align with the findings in this study. Willaarts et al. (2014) highlighted the economic water productivity of various crops in the same region, at the country scale, revealing the low resource-weighted revenue of the four crops analysed in our study, except for tobacco, when compared with other crops cultivated in the same region. In particular, on average over the period 2007–2010, they found values generally around or below $0.1US\$/m^3$ for both coffee and tobacco, in alignment with our results.

Naranjo-Merino et al. (2017) found the average total water footprint for cocoa cultivation in north-eastern Colombia was 18.9 Gm^3 in 2014. The large variability of the yield within the country, also highlighted by the authors, might explain the discrepancy between their sub-national results and our national scale calculation for the same year (30.1 Gm^3). Accordingly, Ortiz-Rodriguez et al. (2015) focused on the assessment of green water efficiency of cocoa production in Colombia and found a theoretical potential between 13.5 and 23.2 Gm^3.

Bulsink et al. (2010) found an average (from 2000 to 2004) of 14.5 Gm^3 and 5.3 Gm^3 of total water use for coffee and cocoa production in Indonesia, respectively. Moreover, the average virtual water export was assessed for coffee (7.0 Gm^3) and cocoa (3.5 Gm^3) over the same period. The study relied on sub-national specific data. Our national scale analysis revealed different results for the average (2002–2004) total water use for cocoa (14 Gm^3) and coffee of (19 Gm^3) production. Virtual water export associated with cocoa (8 Gm^3) and coffee (10 Gm^3) also differed. Finally, cocoa (0.1 Gm^3) and coffee (0.03 Gm^3) virtual water import differed too. These discrepancies arise from the different methods, data sources and scales of analysis.

van Oel et al. (2009b) analysed the average water footprint of the Netherlands for cocoa (0.14 Gm^3) coffee (2.38 Gm^3) and tea (0.46 Gm^3) for the period 1996–2005. Our analysis showed higher results for cocoa (7.3 Gm^3) and lower results for coffee (1.15 Gm^3) and tea (0.16 Gm^3) on average for the period 2002–2005. In this case, methodology, data sources and temporal scope significantly differs from our study, limiting the possibility for direct comparisons.

Comparing our average results for the period 2002–2005 with Mekonnen and Hoekstra, (2011), we found larger global water use linked to cocoa (15%), coffee (3%) and tea (30%) and lower global water use linked to tobacco (−7%). This difference is strictly linked to the different temporal scope of Mekonnen and Hoekstra, (2011) (1996–2005), and our study captured a more recent time period in which global production volumes of the commodities studied were markedly higher.

4. Discussion

Cocoa, coffee, tea and tobacco are among the most widely consumed and traded stimulants. However, as a source of individual and national consumption, stimulants have been peripheral to the agenda on sustainable diets and resource use. This study represents the first attempt to investigate the impacts of these commodities at a global scale, from the perspective of producers and consumers, on water, land and fertiliser use. As the global demand for these resources exceeds their sustainable rate of renewal (Tuninetti et al., 2019; Li et al., 2019; Straaten et al., 2015), understanding the drivers of water, land and fertiliser has become increasingly important. Stimulants, as we show in this study, provide an important sector in the overall management of this demand and the broader challenge of guiding humanity within planetary boundaries.

In 2017, the global consumption of stimulant crops, as shown in Fig. 2, required land equivalent to the land area of Italy (around 29 Mha), and covered around 3% of global cropland cultivated for direct human consumption (FAO, 2020b); a green water volume of 269 Gm^3, accounting for around 5% of global agricultural green water use (Hoekstra and Mekonnen, 2012); and a blue water volume of 6.5 Gm^3, equivalent to around 1% of global agricultural blue water consumption (Hoekstra and Mekonnen, 2012). Whilst, we estimate stimulant crops are responsible for 2.6MT of fertiliser use, equivalent to around 1% of global fertiliser use (IFA, 2020).

Several further insights emerge from our environmental impact assessment of stimulants. First, the water, land and fertiliser demand of stimulants analysed within this study is non-trivial and comparable with the resource footprints of other major global agricultural commodities and even entire countries (see Section 3.1). Moreover, except for tobacco, the resource burden of stimulants has grown substantially in recent decades (Fig. 2). Second, the centres of resource use and demand associated with stimulants implicate a few major countries (see Section 3.2). In contrast to other major agricultural commodity systems, such as maize (You et al., 2014), wheat (Bastiaanssen and Steduto, 2017) and livestock (Poore and Nemecek, 2018; Sporchia et al., 2021a), which involve a greater number of actors, the consolidation of stimulant supply chains offers clear entry points to their management. Third, substantial variation exists within and between the resource use profiles for the four stimulants (cocoa, coffee, tea and tobacco) studied (Fig. 2). This provides potential scope for (i) substitution between stimulant consumption, (ii) supply chain screening of resource-intensive production sources, and (iii) triage-based support for farmers, in order to reduce the resource footprint of stimulant supply chains. Lastly, our economic assessment of average farmer revenues linked to stimulant production reveals that tobacco generally provides the highest returns per unit of resource use, followed by tea, coffee and cocoa, as shown in Fig. 4. However, stimulants are not necessarily the most environmentally and economically efficient compared with other cash crops. For example, an experimental plantain cultivation trial in the tropical climate of western Nigeria observed an economic return per unit of water use between 1.63 and 2.83US$/$m^3$ (Akinro et al., 2012). The comparison between this result with another cash crop largely cultivated in Nigeria, such as cocoa (0.025$/$m^3$) suggests that the allocatibaon of water resources to plantain cultivation in Ghana could be more efficient compared with cocoa. Moreover, trade-offs arise when considering synergies among inputs. Indeed, the correlation between fertiliser application and producer is not linear since to increase the yield and the fertiliser application more labour is required, resulting in higher production costs, and thus lower revenue (Specialty Coffee Association, 2017). In some cases land size is positively correlated with income, but negatively with yield. Also, larger quantities of inputs might be required due to land becoming infertile (Bymolt et al., 2018). For instance, climate change induced changes to rain patterns will not only influence resource use (Chemura et al., 2016), but it will also threaten coffee cultivation by making it more suceptible to coffee pests (Kutywayo et al., 2013), which, in turn, might lencourage greater pesticide use. Consequently, in countries where stimulants provide income for a large amount of the population careful assessment of these future risks and their management is important (Moat et al., 2017).

Studying these synergies and trade-offs in a systematic manner was not possible due to the limited availability of and alignment between economic and environmental data for the commodities studied. Foremost, this study highlights a greater need for further research on the stimulant economy as a source of resource demand and an important target for sustainable natural resource management. Currently, the stimulant economy and its impacts are driven, unpredictably, by volatility in global commodity markets. Although sustainable certification systems have sought to guide the sustainability of production and consumption within this context, they exert minor influence over this system at large and their efficacy has been called into question on the basis of standard dilution, mission drift and incentivisation of cash cropping above other land types (Krishnan, 2017a; Qiao et al., 2016; Bymolt et al., 2018). As such, there is a critical need to implement more stringent measures to moderate resource use driven by stimulant supply chains.

Supply-side policies must regulate the practices promoted by transnational corporations who shape production methods and activities in stimulant supply chains. Trade law, corporate reporting requirements, and fiscal instruments may prove useful towards this end. Demand-side policies are also necessary, particularly since production-based resource efficiencies are not widely observed across the stimulant economy (as shown in Section 3.3). Detailed and accurate sub-national economic and environmental data, not currently available, is needed to design and target such measures. Our findings suggest policy instruments implemented in just a few consuming nations might be sufficient in order to significantly influence global demand for stimulants and their associated environmental impacts (Fig. 3). For instance, Indonesia, the Netherlands, the Ivory Coast, Germany and the US alone account for more than half global consumption of cocoa. The US, Brazil, Germany, Italy, Japan and Ethiopia account for the same share of coffee demand. Whilst China and India alone account for more than half global tea consumption. Moreover, China and India, together with Brazil, account for more than half of the global consumption of tobacco. Guiding sustainable levels of consumption through taxation, quality-based price improvements, or government regulation (in the case of tobacco consumption) (Li and Tang, 2018) may help to moderate demand for stimulants in major countries of consumption, such as the US, China and Brazil, and can also raise revenue for sustainable farming practices, as in the case of Fairtrade, Rainforest Alliance and other certification systems (Ingram et al., 2018; Krishnan, 2017b; Qiao et al., 2016; Bymolt et al., 2018). However, these measures must be implemented with attention to, and input from, stimulant producers to avoid unequal risk and cost sharing (Ochieng et al., 2013). Here, local level evaluation of and consultation with affected actors is necessary, before and after such interventions (Zaehringer et al., 2020), where they have historically been excluded from policy formulation (Elgert, 2012; Garrett et al., 2016).

The findings of this study and their application to policy must be viewed with attention to the uncertainties surrounding environmental footprint assessment. These can be categorised into spatial aggregation, estimation of resource coefficients and linkage to final consumers. First, the lack of sub-national production and trade data linked to the commodities studied prevents a spatially-explicit analysis of their impacts. The use of national economic and environmental accounts assumes a homogeneous distribution of production and resource use within countries of stimulant production. However, as shown in other more detailed case studies of commodity production (Naranjo-Merino et al., 2017; Bulsink et al., 2010; Uwizeye et al., 2020), agricultural regimes are geographically heterogeneous. Reliance on national accounts also assumes all commodity production within countries is produced with the same level of resource efficiency (e.g. water, land or fertiliser use per tonne of output). Variations between farming practices and environment violate this assumption but could not be feasibly captured at the scope of this study (1,753,512 records), nor robustly estimated using sensitivity analysis based on available data. In future, linkage of satellite data to crop production and trade data can help to better trace commodity flows to their production source, offering a more accurate assessment of their impacts (Moran et al., 2020). Lastly, linking these impacts to final consumers is difficult given the long and complex chains of food and beverage supply chains which cannot be fully traced due to the truncated nature of physical economic accounts (Taherzadeh, 2020a). Use of MRIOA which uses financial transactions to extend resource use traceability across a greater supply chain scope might offer a more accurate assignment of responsibility for stimulant production impacts downstream supply chains (Hubacek and Feng, 2016). However, commodity-specific MRIO databases are still not fully developed to enable coverage at the equivalent temporal and spatial scope of our analysis (Taherzadeh, 2020b). Moreover, data pertaining to agri-commodity supply chains is also often proprietary, especially for commodities whose market is controlled by only a few large companies, preventing an accurate identification of supply chain actor responsibility for environmental problems within the stimulant economy.

Notwithstanding these limitations, our findings offer a new, open access database, to understand the scale of and responsibility for environmental impacts in stimulant supply chains. We identify several immediate research needs for the mainstreaming of these findings into the research and policy agenda surrounding sustainable consumption. First, in order to improve the accuracy and policy-relevance of such analysis, further work is necessary to down-scale production, consumption and trade accounts. Second, the extent of substitutability, in both the production and consumption of stimulants is needed to construct a feasible policy landscape for their sustainable management. From a production perspective substitution would entail switching from unsustainable stimulant crops to sustainable crops within a given production region, considering the specific environmental, social and economic local conditions, or increasing the resource efficiencies of stimulant crops under existing cultivation (Li and Tang, 2018). In terms of consumption, substitution invites a shift in the sourcing of crops from less to more sustainable production regimes, within or between different regions (Laven and Boomsma, 2012). As we have shown within this study, decisions made in relation to the stimulant economy can strengthen or weaken humanity's progress in tackling a wide range of environmental issues.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2021.100029.

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