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TECHNICAL NOTE

Forest Footprint for Cities

Methods for Estimating Deforestation and Associated CO_2 Emissions Embodied in Products Consumed in Cities

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Technical notes document the research or analytical methodology underpinning a publication, interactive application, or tool.

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1. INTRODUCTION

With their high concentrations of people, influence, and consumption, cities have an enormous—and growing—impact on climate change. Through initiatives like C40 Cities, the Global Covenant of Mayors for Climate and Energy, the World Mayors Council on Climate Change, and the Race to Zero campaign, many cities are setting their own agendas to combat climate change. However, an acknowledgment that cities have substantial impacts on climate and the environment far outside their own borders is just starting to gain traction. Cities' actions, both inside and beyond their boundaries, will be key to meeting the climate action targets set by national and international agreements. New tools such as the Greenhouse Gas Protocol's Supplemental Guidance for Forests and Trees are essential to help communities understand how implementing nature-based solutions within their boundaries can contribute to achieving their climate goals.[1] The Forest Footprint for Cities can provide a complementary method for understanding how city actions impact trees and forests outside their boundaries.

Tropical forest loss is a major contributor to climate change, representing 8–11 percent of global greenhouse gas (GHG) emissions annually (Seymour and Busch 2016; IPCC 2022). Nature-based solutions, including halting deforestation and allowing degraded forests to recover, could contribute as much as 30 percent of the CO_2 mitigation necessary to achieve 1.5°C stabilization (Roe et al. 2019). However, global trends are moving in the opposite direction, with the tropics losing 11.1 million hectares of tree cover in 2020 (GFW 2022). Commercial production of widely used commodities, such as soy, beef, palm oil, and wood fiber, remains the leading driver of tropical deforestation (Curtis et al. 2018; Goldman et al. 2020). Due to the remoteness of tropical deforestation, it is often difficult for those living in cities to comprehend the magnitude of the issue or how they might be contributing to it.

The Forest Footprint for Cities methodology connects global estimates of tropical and subtropical deforestation linked to agricultural production to commodity-specific international trade and city consumption. The methods ultimately present the city's Forest Footprint in terms of hectares (ha) of embodied deforestation (ED) consumed and the associated CO_2 emissions. Here, ED is defined as deforestation that is attributed to tropical and subtropical forest being cut and replaced by a certain commodity. The omission of ED emissions from most cities' GHG inventories highlights the need for climate action planning to expand beyond the boundaries of city jurisdictions.[2]

The main goals of this approach are to raise awareness of the scale of the overall impact of urban consumption on tropical and subtropical forests and to help cities focus their climate mitigation actions on high impact commodities. The Forest Footprint for Cities is intended primarily for use by city government officials; however, secondary users may include nongovernmental organizations and corporations. The Forest Footprint shows

- the hectares of ED, by commodity, consumed within the city (ha/capita);
- the approximate area of deforestation linked to city consumption of those commodities (ha/yr); and
- the resulting carbon dioxide emissions from embodied deforestation (tCO_2/yr).

To make the Forest Footprint accessible to its target audiences, the output will be presented via the Forest Footprint for Cities Dashboard web application. The Dashboard will allow those without a technical background to understand the impact that city consumption has on tropical and subtropical forests through everyday consumption and to visualize how reducing the volume or the impact of specific commodities might change the footprint. The Forest Footprint for Cities methodology and Dashboard aim to present a compelling, data-driven call to action for cities to take steps to reduce their impact on tropical and subtropical deforestation.

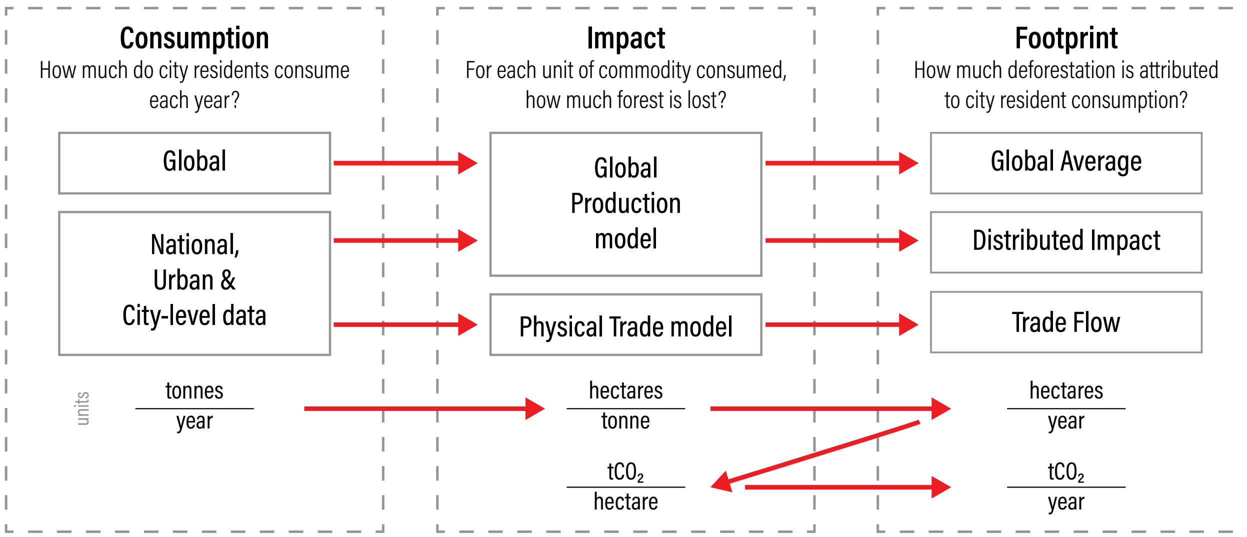
This technical note explains the methods used to calculate cities' Forest Footprints. We use the term Forest Footprint in this technical note to refer to both the methodology and its outputs (i.e., hectares of deforestation and tonnes of CO_2 emissions (tCO_2) associated with consumption of ED). Section 2 provides an overview of methods used for calculating the Forest Footprint and outlines in more detail the data and calculations involved in each component. Section 3 explains how city-level consumption of the commodities included in the Forest Footprint methodology is estimated; and Section 4 describes how questions of attribution and traceability are addressed. Section 5 describes the final calculation of the Forest Footprint; and Section 6 outlines how GHG emissions associated with ED are calculated. Finally, Section 7 discusses comparisons, assumptions, and limitations.

2. OVERVIEW OF METHODS

The Forest Footprint for Cities focuses on tropical and subtropical deforestation, where deforestation is defined as the permanent land-use change from forest land to crop, pasture, or plantation forest land (Pendrill et al. 2019a, 2019b, 2020). While this includes some temperate regions (i.e., Chile, Australia, New Zealand, and Japan), the majority of temperate and boreal forests are excluded from this analysis as there is little permanent deforestation in these forests (Curtis et al. 2018). Further, what data exist on deforestation in temperate and boreal forests is not able to be parsed out into commodity-specific drivers of deforestation as in Pendrill et al. (2019a, 2019b, 2020). Temperate and boreal forest loss and degradation are important issues; however, the vast majority of recent forest loss in these areas is attributed not to food products (as with tropical and subtropical deforestation) but to timber harvesting in managed forests (Curtis et al. 2018; Goldman et al. 2020; Hoang and Kanemoto 2021). As forests that are harvested in temperate and boreal zones are likely to be replanted or naturally regenerated, this forest loss falls outside the scope of the Forest Footprint methodology.[3]

The Forest Footprint methodology is based on four main calculations. The first calculation is the annual city-level consumption of all commodities (given in tonnes per year) known to be linked to deforestation. The second calculation is the specific area of tropical and subtropical deforestation (given in hectares per year) associated with the production of each of those commodities (given in tonnes); the area is calculated through impact models. The third calculation is the city's total Forest Footprint, estimated by multiplying the city-specific consumption of each commodity (tonnes/year) by the associated impact models to produce a Forest Footprint (ha/year). Carbon dioxide emissions are then calculated based on the Forest Footprint calculations.

Figure 1 | **Simplified Methodology of the Forest Footprint**



Note: The arrows indicate how each of the three Footprints was calculated (e.g., the Global Average Footprint uses the global consumption calculation and the Global Production Model). The bottom part of the diagram shows how units were converted.

Source: Authors.

2.1 Calculating annual rate of city-level consumption of commodities

The Forest Footprint methodology uses national-, urban-, and city-level consumption data, which allows for footprints to be calculated when data at higher levels of geographical specificity (e.g., city level) are unavailable. Commodities for which consumption data are calculated include beef, soy, palm oil, wood fiber, cocoa, coffee, rubber, sugar, and other crops. City-level consumption of these commodities is calculated in one of two ways based on data availability: absolute consumption (i.e., tonnes per capita of a specific commodity) or, when these data are unavailable, consumption ratios, which estimate the differences between subnational consumption and national consumption (e.g., dividing city-specific fuel expenditure by national fuel expenditure would provide a ratio with which subnational consumption of biofuel based on palm or soy oil can be calculated). Thus, the Forest Footprint provides cities with footprint estimates that can then be further refined.

2.2 Calculating area of tropical and subtropical deforestation associated with each unit of commodity consumed, or "impact models"

Data from the Land-Balance Deforestation Attribution Model (LanBaDA) are used to calculate the ED in both hectares and tonnes of CO_2 emissions associated with a unit of commodity produced (Pendrill et al. 2019a, 2019b, 2020). LanBaDA uses global land-use data from FAO (2020)—which is based on annual national surveys from FAO's Forest Resources Assessment and FAO's Land Use, Irrigation and Agricultural Practices questionnaire—and tropical and subtropical forest loss data from Hansen et al. (2013) to estimate the area of tropical and subtropical deforestation associated with the production of commodities. Based on these data, the Forest Footprint is able to utilize two different methods to attribute deforestation to consumption: the Global Production Model, which represents an even distribution of deforestation (both tropical and subtropical) across analyzed commodities produced globally; and the Physical Trade Model, which separates the consumption of commodities whose production is linked or not linked to tropical and subtropical deforestation through the use of international trade data.

Table 1 | **Comparison of the Different Footprint Variants**

FOOTPRINT NAME	FOOTPRINT DESCRIPTION	FOOTPRINT RELEVANCE AND LIMITATIONS
Global Average	Consumption: This calculation assumes the equal consumption of commodities per person worldwide. Impact: This calculation uses the global average deforestation impact for each commodity (by weight or volume units), regardless of its country of production.	This calculation is a useful benchmark, as the per capita rate is the same worldwide. It provides an estimate that would be valid in a closed-system view where all consumption and deforestation is accounted for with no leakage. It does not account for the significant differences in consumption rates from one city to another or differences in production based on differing geographies or jurisdictions.
Distributed Impact	Consumption: This calculation estimates the city's unique consumption patterns based on available national or subnational data. Impact: This calculation uses the global average deforestation impact for each commodity (by weight or volume units), regardless of its country of production.	By assuming the maximum liquidity of commodities traded in global markets (i.e., where increased consumption of American soybeans or beef in the U.S. increases global demand and incentivizes deforestation for soy farms and ranches in Brazil and Indonesia [see Box 1]), this calculation is better able to account for the impacts of city-specific consumption patterns on tropical and subtropical deforestation based on the assumption that global demand is not impacted by any individual city's consumption.
Trade Flow	Consumption: This variant calculates consumption based on national-level commodity imports via the Physical Trade Model and subnational consumption data, then factors for city population. Note that in this unique case the impact model (Figure 2) affects how the consumption model calculates consumption. Impact: This calculation takes into account the country of origin of all commodities and traces the deforestation impact attributed to each using the Physical Trade Model.	This calculation begins with country-specific data on production, imports, and attributable deforestation of all commodities, thereby offering a high degree of specificity and accuracy on some commodities. It does not account for consumption that eludes commodity tracking, commodities that are embedded in other imports, or indirect deforestation due to global market liquidity.

Source: Authors.

2.3 Calculating a city's Forest Footprint

The Forest Footprint estimate represents the ED in products consumed in a given city. It is based on an average of three distinct footprint variants—Global Average, Distributed Impact, and Trade Flow—each of which is calculated based on different combinations of consumption calculations and impact models (Figure 1). This flexibility allows cities to compare and contrast the impacts of their consumption on tropical and subtropical forests, based on the different assumptions of these models.

These footprints align roughly with the three footprints proposed by the European Commission (2013, 97) but are based on simpler methods of estimation. Together, these footprint variants are intended to give city staff and residents a more comprehensive understanding of their impact on tropical and subtropical forests. The different footprint calculations are summarized in Table 1.

As Figure 1 and Table 1 show, the Global Average Footprint calculation uses global consumption data, while the Distributed Impact and Trade Flow Footprints can use national-, urban-, or city-level consumption data. For the purposes of this technical note, "urban" refers to data representing all urban areas within a given country, whereas "city" refers to consumption data specific to a given city.[4] City population is determined from Natural Earth's Populated Places data set, which provides city populations for the 500 most populous global cities.[5]

2.4 Calculating a city's CO_2 emissions estimate based on its Forest Footprint calculation(s)

CO_2 emissions are calculated as a range of per-hectare values from recent (2005–17) tropical and subtropical deforestation taken from Pendrill et al. (2020), who use aboveground biomass estimates from Zarin et al. (2016) and belowground biomass estimates from Mokany et al. (2006). The Forest Footprint methodology also includes emissions estimates that incorporate carbon opportunity costs (i.e., forgone carbon sequestration [see Searchinger et al. 2018; Waite et al. 2019]). Emissions from deforestation and carbon opportunity costs are presented separately to communicate the total annual CO_2 emissions from consumption of ED and wider agricultural land-use emissions for the city in question.

The following sections (3–6) describe each of these four calculations in more detail.

3. ESTIMATING CITY RESIDENTS' CONSUMPTION

The first step of the Forest Footprint calculation involves estimating the per capita consumption of key forest-risk commodities by city residents. At the finest level of geographic specificity (city level), the Forest Footprint calculates an average city resident's consumption profile for each commodity. This is the preferred form of consumption data (see Table 2), but data are not always available at this level of detail and resolution. Census and survey programs often report data by category, not by specific commodity (e.g., money spent on meat and meat products rather than beef), and many commodities are embedded within other products, making their actual consumption difficult to deduce (e.g., palm oil in processed foods and cleaning products).

Table 2 | **Types of Consumption Data and Their Preferred Order of Use**

DATA TYPE	METRIC	SCOPE	PREFERRED ORDER OF USE	EXAMPLE
Direct commodity-specific consumption	Fresh weight (e.g., tonnes, kilograms per capita, etc.)	City and commodity specific data	1	Tonnes of coffee consumed in city A
		Consumption data for all urban areas in country of interest	2	Tonnes of chocolate consumed in all urban areas of country B
Consumption of product categories which include desired commodity but cannot be disaggregated[a]	Fresh weight (e.g., tonnes, kilograms per capita, etc.)	Commodity-specific city- and national-level data	3	1.0 kg of red meat[b] consumed per capita per year in country B and 1.2 kg of red meat consumed per capita per year for city A (located in country B) would produce a city-level ratio of 1.2
		Commodity-specific urban- and national level data	4	
	Data provided in metrics other than fresh weight (e.g., USD expenditure per capita)	Commodity-specific city- and national level data	5	US$1000 spent on red meat per household per year in country B and $1200 spent on red meat per household per year for city A (located in country B) would produce a city-level ratio of 1.2
		Commodity-specific urban- and national level data	6	
General consumption metrics which include desired commodity but cannot be disaggregated[1]	Data provided in metrics other than fresh weight (e.g., USD expenditure per capita)	Commodity-specific city- and national level data	7	$2000 in total household expenditure per household per year in country B and $2500 in total household expenditure per household in city A (in country B) would produce a city-level ratio of 1.25
		Commodity-specific urban- and national level data	8	

Notes:

a These data types are used to calculate consumption ratios, which make use of consumption data that are otherwise unable to be disaggregated into fresh weight of a commodity. Thus, both national- and subnational-level data are used to convert national-level direct consumption data to subnational levels.

b Following COICOP-based reporting, the red meat category includes both beef and many other forms of red meat (e.g., mutton, pork, etc.).

Source: Authors.

In instances where city-level consumption data are unavailable, a hierarchy of consumption ratios (calculated at different levels of geographic aggregation) is used to develop appropriate estimates based on the best data available. These consumption ratios are similar in nature to those used in the Ecological Footprint (Wackernagel et al. 2006; Rees and Wackernagel 2008), which were developed to analyze the consumption of energy, water, and food in cities from national-level data (see also Moore et al. 2013; Goldstein et al. 2016; Baabou et al. 2017). The preferred order of use for different types of consumption data within the Forest Footprint methodology is shown in Table 2.

3.1 Products Used to Calculate Consumption of Commodities

In order to calculate the quantity of commodities consumed within a city, it is necessary to understand the forms in which they are consumed. Here we identify some of the key products used to determine subnational consumption of each commodity either directly or via consumption ratios. This section also describes how the calculation of commodity consumption differs slightly when used in the Distributed Impact versus the Trade Flow Footprint variants (for the Global Average Model, no calculation is necessary since consumption under this model is the same for all countries and cities).

Box 1 | Consumption Calculations for Main Commodity Categories

Soy: Soy is both a food and a fuel source for humans. As a food source, it is consumed directly in products such as tofu and indirectly through consumption of meat and dairy that were raised on soy livestock feed consumption. Of the total global soy supply, approximately 13 percent is used for direct human consumption, 17 percent is used as a biofuel feedstock, and 70 percent is used as animal feed (Potts et al. 2014). Soybean oil is a common feedstock for biofuels, representing 27 percent of global biodiesel feedstock use (Steinweg et al. 2019).

While the Trade Flow Footprint can track soy meal consumption at the national level, we account for embodied soy meal consumed through meat and dairy in the Distributed Impact Footprint at the national level using a less direct method. As values of soy meal consumed per unit of livestock produced vary widely, national rates are used for the Distributed Impact Footprint when such data are available (e.g., IFIF 2022); in the event that appropriate figures are unavailable, the soy meal content of meat consumption is estimated based on average values from Table B-1, which give the amount of soy meal needed to produce one unit of livestock product for beef and veal, pork, poultry, eggs, and milk based on EU and U.S. data. When local feed conversion rates are not available, EU rates are used for European cities, the U.S. rates for American cities, and the EU-U.S. average rates for cities in all other countries. Estimates of soy meal consumption through meat and dairy products should be checked against national soy meal consumption data for accuracy; however, producers in certain countries may not use soy meal for feed at all. This method is used for calculating direct consumption at all levels for the Distributed Impact Footprint calculation and may also be used as a consumption ratio for the Trade Flow and Distributed Impact Footprint calculations.

Palm Oil: On a global scale, palm oil is used more than any other vegetable-based oil in food products, accounting for one third of global vegetable oil production (Potts et al. 2014). Palm oil is consumed directly in processed food, as an ingredient in household products like soaps and cosmetics, and in biofuels. As Pendrill et al. (2019a) and Proforest (2011) note, the highly processed nature of these products makes estimating the consumption of palm oil difficult but not impossible. Palm oil is important as a feedstock for biofuels, representing 15.1 percent of global biofuel market volume share in 2019 (Grand View Research 2020) and 53 percent of the EU's palm oil imports (Oil World 2019).

Beef: Meat, leather, and dairy are three commodities associated with the deforestation caused by expansion of pastureland for cattle ranching; however, we include only meat in this category. Based on Brugnoli and Král' (2012) and Gac et al. (2014), Pendrill et al. (2020) attribute around 95 percent of ED to beef raised on pastureland. The remaining 5 percent is attributed to leather, as most leather comes

TABLE B-1 | Soy Meal Consumption via Meat Products Used in the Distributed Impact Footprint (beef and veal, pork, and chicken)

PRODUCT		SOY MEAL PER UNIT OF PRODUCT		
		EU	U.S.A.	EU-U.S. AVERAGE
Beef and Veal		232 g/kg	77 g/kg	155 g/kg
Pork		648 g/kg	508 g/kg	578 g/kg
Poultry	Chicken	967 g/kg	788 g/kg	878 g/kg
	Turkey	n/a	1079 g/kg	1079 g/kg
Eggs		32 g/egg	28 g/egg	30 g/egg
Dairy	Milk	21 g/L	37 g/L	29 g/L
	Cheese	186 grams/kg	n/a	186 grams/kg

Sources: E.U. data from van Gelder et al. (2008); U.S. data from Decision Innovation Solutions (2021) and FAO (2020).

from beef cattle. Following Pendrill et al. (2020), consumption of leather is not accounted for within the footprint, because trade in genuine leather products is difficult to trace, as it is often grouped with composite leather in data (e.g., by UN COMTRADE).

While dairy products are often also associated with other consumption-based carbon footprinting endeavors, following Opio et al. (2013), Pendrill et al. have not attributed any deforestation to dairy products, because they "assume that pasture expansion into forests is primarily for extensive cattle grazing for meat production (and not dairy products)" (2019b, 3). Dairy products in some cases may represent significant risk of increasing consumption of ED—for example, when dairy cattle are fed soy meal or palm kernel meal—however, the Footprint accounts for this through soy and palm oil consumption.

Wood Fiber: In 2015, industrial roundwood accounted for one third (429 million m^3) of tropical and subtropical production of primary timber products, with fuelwood comprising the remaining two thirds (around 1 billion m^3) (Held et al. 2021, based on FAO 2020). The Forest Footprint methodology considers wood used for construction, commercial fuelwood, and paper and paperboard. Plantation forestry has been a significant driver of deforestation in tropical and subtropical forests, where primary forest is cleared to establish fast-growing tree farms (Heilmayr 2014; Davis et al. 2015; van Straaten et al. 2015). Based on Pendrill et al.'s (2019a) LanBaDA model, only areas converted from unmanaged to plantation forests are identified as ED.

Cocoa, coffee, rubber, and sugar: These commodities have smaller impacts on tropical and subtropical deforestation compared to the previous commodities but are more commonly associated with tropical deforestation than the Other Crops category and have higher per unit impacts per unit of fresh weight. Globally, 92 percent of cocoa produced is exported, with European and North American markets consuming the majority (FAO n.d.). Coffee consumption is not dissimilar, with importing countries representing 70 percent of yearly global consumption (ICO 2020). Sugar is largely produced in tropical and subtropical countries, with around 22 percent in 2017–19 being used for ethanol production (OECD and FAO 2020). China is the world's largest consumer of natural rubber, where around 70 percent of natural rubber is used in tires and tubes (Statistics and Planning Department, Rubber Board 2018). Other products using natural rubber not accounted for by the Forest Footprint include latex, technological products, food storage, and adhesives. These four commodities are calculated and presented separately within the Forest Footprint.

Other Crops: This category represents crops that are not commonly associated with tropical and subtropical deforestation and therefore represent a small fraction of ED. These crops are mostly food products, as well as fiber crops used for clothing and household textiles. As the category represents more than 100 individual commodities, these have been grouped together in the Forest Footprint.

Consumption data are reported in various forms depending on the commodity and the data source and often require processing to transform raw data into the desired metric of tonnes consumed per capita per year. This is because commodities are consumed in different forms (e.g., palm oil can be consumed as food, fuel, and in household products), and consumption is measured in different ways (i.e., as money spent on a commodity or as nutritional intake in the form of a commodity). Further, the absolute quantity consumed (e.g., palm oil in soaps) is generally not accounted for directly, as the content of commodities in these products varies widely, is often difficult to calculate, and has little effect on city footprints. Instead, many of these product categories are captured in the calculation of subnational consumption ratios (see Section 3.4 for further explanation). Table 3 outlines the general breakdown of commodities, subcategories, and product categories used. Box 1 provides more detail on how consumption for each commodity was calculated.

3.2 Calculating National Absolute Consumption

In most cases, consumption of commodities is estimated at the national level to provide a reference for, or to represent, city-level consumption when city-level data are unavailable. The Distributed Impact Footprint calculates national apparent consumption using UN COMTRADE and FAOSTAT as primary sources of commodity-production, import, and export data. Apparent consumption is the sum of annual production and imports minus all exports; it differs from absolute consumption data in that it does not measure consumption directly (e.g., how much beef residents of a given country eat per year) but indirectly (e.g., how much beef is available for residents of a given country to eat per year after trade is accounted for). Commodity-specific consumption data from national agencies and other credible sources are used to validate these calculations; however, such data may not always be available. In circumstances where UN data differ from national factors of production, import, export, and consumption data may be averaged after confirming the comparability of measurements.

Table 3 | **Products and Product Categories Indicating Consumption of Commodities**

COMMODITY	COMMODITY SUBCATEGORIES	PRODUCTS USED TO CALCULATE ABSOLUTE CONSUMPTION	PRODUCT CATEGORIES USED TO CALCULATE SUBNATIONAL CONSUMPTION RATIOS[f]
Soy	Food	Soybeans,[a] soybean oil[b, e]	
	Livestock feed	Soy meal, beef, chicken, pork, milk, eggs, cheese[b]	Beef,[c, e] chicken,[c] pork[c]
	Biofuel	Soybean oil,[b, e] biofuels[b, e]	Liquid fuels[c, e]
Palm Oil	Food	Palm oil,[a] palm kernel oil [a, b]	Vegetable oils;[c,] other appliances, articles, and products for personal care[c]
	Livestock feed	Palm kernel meal[b]	Beef[c, e]
	Biofuel	Biofuels[b, e]	Liquid fuels[c, e]
Beef	Food	Beef, meat of other bovine animals,[b] meat preparations of bovine animals[b]	Live animals, meat, and other parts of slaughtered land animals[c]
Wood Fiber	Wood for construction	Roundwood,[b] sawnwood,[b] and wood-based panels[b]	Construction, expenditure on wood products by construction sector
	Fuelwood	Fuelwood,[b] charcoal,[b] wood pellets[b]	Solid fuels,[c] type of energy use by household
	Paper and paperboard	Newsprint, paper, and paperboard[d]	
Rubber		Rubber (natural),[a] tires[c]	Purchase of vehicles[c]
Cocoa		Cocoa paste, cocoa butter, cocoa powder, chocolate, cocoa drinks,[c] cocoa, and cocoa-based food products[c]	
Coffee		Coffee (green)[b]	Coffee and coffee substitutes[c]
Sugar		Sugar[b]	Sugar, confectionery, and desserts;[c] liquid fuels[e]
Other Crops	Tobacco	Tobacco (unmanufactured)[a, b]	Tobacco[c]
	Spices	The full list of products included in this category is provided on the Forest Footprint dashboard webpage.[g]	Spices, culinary herbs, and seeds[c]
	Other cereals		Cereals and cereal products[c]
	Rice		
	Roots and tubers		Tubers, plantains, and cooking bananas[c]
	Pulses		Pulses[c]
	Fiber crops		Clothing,[c] household textiles[c]
	Oilseeds		Vegetable oils,[c] liquid fuels[e]
	Tree nuts		Fruits and nuts[c]
	Fruits		
	Vegetables		Leafy or stem vegetables,[c] fruit-bearing vegetables,[c] green leguminous vegetables,[c] and other vegetables[c]
	Crops nec[h]		Stimulants[c] and spices[3]

Notes:

a Category included under "Food" in the FAO New Food Balances database (FAO 2020).

b Category from UN COMTRADE database (UN 2015).

c A COICOP category often used in household consumption surveys. Because these data are usually given in terms of monetary value, they are often better taken as consumption indicators than as products.

d To avoid double counting, we omit "Wood pulp" and "Chips and particles" otherwise included in Kastner et al.(2011a), as the Footprint considers final consumption of paper and not pulp.

e To avoid double counting, we use country-specific profiles to determine the attribution of product consumption (e.g., biofuels based on palm oil or soybean oil) to the appropriate commodities.

f These products and categories are used to calculate commodity-specific consumption ratios at subnational levels. See Section 3.4 for further detail.

g The Forest Footprint dashboard can be found at www.forestfootprint.org.

h "Not elsewhere classified."

Source: Authors.

National-level apparent consumption (C_{napp}) is calculated as follows:

(1)

$$C_{napp} = P_{nat} + I_{nat} - E_{nat}$$

Where P_{nat}, I_{nat}, and E_{nat} represent national production, imports, and exports of a given commodity, respectively.

The Trade Flow Footprint calculation, on the other hand, tracks the international trade of commodities from the country of production to the country of final consumption. National consumption is taken directly from Pendrill et al. (2020), which provides hectares of ED and the associated GHG emissions instead of fresh weight of commodities consumed. For both Distributed Impact and Trade Flow, national consumption provides a basis for subnational consumption ratios to be applied.

3.3 Calculating Subnational Absolute Consumption

The most accurate data for the purpose of the Forest Footprint methodology is per capita consumption of individual commodities for the city of interest. Types of data sources that report subnational data are household surveys (e.g., household income and spending, health, and nutrition), economic surveys, and research publications (e.g., food recall surveys). Data from these surveys and publications can be reported for specific cities, urban areas, or aggregated into total national urban areas. When data are reported for specific cities, per capita consumption for that city is calculated. When data are reported for urban areas, per capita consumption is calculated for the country's total urban population.

3.4 Calculating Commodity-Specific Consumption Ratios

For instances where city-specific or urban estimates of consumption are difficult to source in fresh weight or are included in product categories that are difficult to disaggregate by commodity (e.g., sugar, confectionery, and desserts), urban- and city-level estimates are calculated from national consumption using consumption ratios based on other commodity-specific data, such as household expenditure data or economic censuses. For example, the ratio of average annual household beef expenditure within a specific city to the national average expenditure is used to define the beef consumption ratio for that city. These ratios are used to scale national-level consumption data to the city or urban level (e.g., \$400 spent on vegetable oils per capita in country X and \$600 spent on vegetable oils per capita for city Y located in country X would allow direct or apparent national palm oil consumption to be brought to the city level by a factor of 1.5). Whenever possible, data sets that include both national and either urban or city figures are prioritized over combinations of different data sets (e.g., city-level data from one source and national from another), as this assures that data used in subnational conversions are as consistent as possible. The Commodity-Specific Consumption Ratio (CR_{com}) is calculated as follows:

(2)

$$CR_{com} = \begin{cases} \frac{Exp_{city}}{Pop_{city}} \div \frac{Exp_{nat}}{Pop_{nat}} & \text{if } Exp_{city} \text{ is available} \\ \frac{Exp_{urb}}{Pop_{urb}} \div \frac{Exp_{nat}}{Pop_{nat}} & \text{otherwise} \end{cases}$$

Where city-level and urban-level average household expenditure is given by (Exp_{city}) and (Exp_{urb}), respectively, and is measured against average national expenditure (Exp_{nat}) and the relative size of the city population to the national population (Pop_{city} and Pop_{nat}).

3.5 Calculating the Urban Expenditure Ratio

In cases where few data on commodity-specific city or urban consumption exist, the Forest Footprint uses a general urban consumption ratio (representing total consumption as opposed to commodity-specific consumption) to estimate urban-level consumption of a given commodity. The Urban Expenditure Ratio (EF_{urb}) is calculated as follows:

(3)

$$EF_{urb} = \frac{Exp_{urb}}{Pop_{urb}} \div \frac{Exp_{nat}}{Pop_{nat}}$$

Where EF_{urb} represents a ratio of urban and national total household consumption expenditure (Exp_{urb} and Exp_{nat}) at purchasing power parity provided by World Bank (2021b) or other international sources (OECD 2021 or EUROSTAT 2021). This ratio is taken from total household expenditure and considers differences in urban and national purchasing power parities. Thus, this ratio does not reflect the consumption of any one or group of commodities, but rather of all commodities and other products (e.g., electronics, medication, and clothes).

4. FOREST IMPACT MODELS

In estimating a city's Forest Footprint, it is necessary to determine the amount of ED (given in hectares) attributed to each unit (given in tonnes) of each crop consumed and address questions regarding the international trade of commodities that are inherent in the modeling. As the goal of the Forest Footprint is to show the impact of city consumption on tropical and subtropical forests, the Footprint considers only *tropical and subtropical* deforestation linked to the expansion of agricultural lands and forest plantations.

4.1 Attribution

To estimate the amount of tropical and subtropical deforestation linked to agricultural production and forest plantations globally, the Forest Footprint uses deforestation attribution data from Pendrill et al. (2020). These data build upon two previous studies (Pendrill et al. 2019a, 2019b), which provide more detailed methodological explanations. Pendrill et al.'s LanBaDA model is based on two main premises: first, "where cropland expands, it first expands into (converts) pastures (if there was a gross loss of pasture area) and then into forests (if there was a gross forest loss);" second, "where pastures and forest plantation areas expand they primarily replace forest land" (2019a, 3). Given these assumptions, the quantity of forest loss from cropland, pastures, and forest plantations is attributed to commodities (soy, palm oil, hotspot crops, and other crops; beef; and wood, respectively) "in relative proportion to their expansion in area" (Pendrill et al. 2019a, 4). This attributed deforestation is then amortized over five years of the commodity's production following the deforestation event (Pendrill et al. 2019b).[6]

Approximately 49 percent (on average) of tropical and subtropical forest loss (defined by Hansen et al. 2013) is not attributable to the above categories and is not necessarily considered permanent land-use change or deforestation (Pendrill et al. 2020). Within the Forest Footprint, the Other Forest Loss category represents the impact that humans have on tropical and subtropical forests outside of the ED attributed to the production of commodities—an important action point for cities globally. This category (defined in Pendrill et al. 2019a) includes the influence of a number of other drivers of deforestation, such as urban expansion and wildfires, as well as mining, infrastructure, oil and gas operations, and underreported land-use change unaccounted for in the previous categories. Because of the complexity of attributing Other Forest Loss to city-level consumption, we divide global Other Forest Loss by global population, and attribute it as a global per capita average to urban residents of any city in our methodology.

4.2 Traceability and Impact Models

The Forest Footprint employs two different approaches to trace the deforestation from the source of production to the source of consumption:

- The first approach is based on the Global Production Impact Model, which attributes tropical and subtropical deforestation to global production of a given commodity, regardless of where the commodity was sourced. This allows for the capture of indirect effects that the global market produces (e.g., the pressure of U.S. consumption of soy on Brazilian or Indonesian soy expansion) that are difficult to capture in detailed trade models. This approach is used for the Global Average and Distributed Impact Footprints.
- The second approach builds on Pendrill et al.'s (2019a) Physical Trade Model, which is used only in the Trade Flow Footprint. This model tracks national-level consumption of commodities from specific source regions with their respective differing deforestation factors.

At the national level, the Global Production Impact Model uses a simplified set of assumptions in calculating the hectares of ED associated with the consumption of a given commodity. Tropical and subtropical deforestation per commodity is summed and divided by total global production to create a Forest Impact Factor (e.g., the Forest Impact Factor of soy is 1.46 hectares per tonne, meaning an average of 1.46 hectares are deforested in tropical and subtropical regions for every tonne of soy produced in dry weight based on a five-year amortization rate). This is given in the equation below:

(4)

$$FI_{com} = ED_{com} \div P_{com}$$

Where FI_{com} represents the Forest Impact Factor, ED_{com} represents the total hectares of ED linked to a given commodity using the Global Production Model, and P_{com} represents the total annual global production of the given commodity and its secondary products. The Global Production Model assumes that all soy—regardless of the location of its consumption or production—is linked to the same amount of deforestation (see Box 2).

Table 4 provides an overview of the total deforestation linked to each commodity and its resulting Forest Impact Factor as calculated through the Global Average Model. We chose to use ED based on a yearly average from 2005–17 as opposed to 2017 alone as the average represents a better basis for informing decisions due to yearly fluctuations in ED.

Table 4 | **Deforestation Impacts of Footprinted Commodities, Based on the Global Production Model**

COMMODITY		TOTAL TROPICAL AND SUBTROPICAL ED, 2005-17 AVG. (kha[a])	TOTAL GLOBAL PRODUCTION, 2005-17 AVG. (Mt[b])	FOREST IMPACT FACTOR, 2005-17 AVG. (m^2/t)[c]
Soybeans		390	267	14.6
Palm Oil		423	51	82.9
Beef		1,984	68	291.8
Wood Fiber		598	2,534	2.4
Cocoa		59	4.5	132.2
Coffee		40	8.5	47.0
Rubber		54	11.8	45.4
Sugar		37	1,981	0.2
Other Crops	Rice	221	709	3.1
	Other cereals	444	1898	2.3
	Oilseeds nec	214	238	9.0
	Pulses	146	72	20.0
	Roots & tubers	226	779	2.3
	Vegetables	52	946	0.6
	Fruits	57	761	0.6
	Tree nuts	5	14	3.5
	Fiber crops	2	77	0.3
	Crops nec[d]	31	24	12.6
	Other Crops Total	1,426	5,519	2.6
Other Forest Loss		3,911	-	5.1[e]

[a] *kha = kilohectares.*

[b] *Mt = megatonnes.*

[c] *For the purposes of this table, the Forest Impact Factor, while normally calculated in hectares per tonne, has been presented in square meters per tonne to improve legibility and comprehension.*

[d] *Pendrill et al.'s (2019b) category of the same name includes cocoa, coffee, and rubber, which have been separated in the Forest Footprint. Remaining in this category are tobacco and spices.*

[e] *The Forest Impact Factor for Other Forest Loss is given here in square meters per capita.*

Sources: Tropical and subtropical data were derived from Pendrill et al. (2020) and global production data from FAOSTAT.

The Physical Trade Model uses FAOSTAT international trade data on roughly 400 items to trace the deforestation associated with the production of commodities to the country of their consumption (Pendrill et al. 2019b). The model is based on studies by Kastner et al. (2011b, 2014a), which convert products into "physical units of primary commodity equivalents" (e.g., 400 g cocoa per 1 kg of chocolate) to avoid double counting. This ensures that commodities that are processed in country A and exported as different products to country B (e.g., cocoa beans processed into chocolate) are discounted by the correct ratio from country A's total consumption of ED (since the chocolate would be consumed in country B). To determine a country's final consumption of ED, Pendrill et al. (2020) then convert the "physical units of primary commodity equivalents" associated with tropical and subtropical deforestation into the area of ED via FAOSTAT crop yield data (given in tonnes per hectare).

The Physical Trade Model has certain advantages over the Global Average Model; for example, it better accounts for trade in commodities embodied in certain products, such as bread and pasta, but not heavily processed products, such as frozen pizzas and soaps.[7] At the same time, as Pendrill et al. (2019b) acknowledge, the Physical Trade Model estimates that countries that import livestock feed products (e.g., soy meal) consume more ED than countries that import meat products from livestock that grazed on these feed products; however, the authors claim the discrepancy is marginal. Furthermore, there remain significant differences in the results of different trade model methodologies (e.g., FAOSTAT, Multi-Regional Input Output (MRIO) modeling, and physical trade modelling), which are not yet fully understood (Kastner et al. 2014b). It is important to note when analyzing a city's Forest Footprint that this model should not be considered superior—but rather complementary—to the Global Production Model.

5. CALCULATING FOREST FOOTPRINT VARIANTS

The Forest Footprint is calculated using three variants. Each variant taken on its own gives city officials the opportunity to understand the different assumptions used to calculate their Forest Footprint. When averaged, the footprint variants present the city's impact in a simpler and more harmonized fashion. This supports the main goal of the footprint—namely, to raise awareness and empower city leaders and officials to support tropical and subtropical forests. In doing so, cities can avoid some of the common pitfalls of acting on a footprint (Chapman et al. 2017). This aligns with Pendrill et al. (2020), who warn that "the estimates of deforestation embodied in import should therefore be interpreted as a measure of deforestation risk."

The Forest Footprint variants may be assessed using consumption data at different levels of geographical specificity, as available: global, national, urban, and city. While each level gives a city-specific footprint, per capita consumption rate estimates may differ depending on whether they are calculated with global-, national-, urban-, or city-level averages. The first two footprints—Global Average (equation 5) and Distributed Impact (calculated at three different scopes in equations 6–8)—give footprints to cities based on the Global Average Model, while the Trade Flow Footprint (also calculated at three different scopes in equations 9-11) is based on the Physical Trade Model.

5.1 The Global Average Footprint

The Global Average Footprint assumes equal consumption of commodities per person worldwide and equal distribution of deforestation impacts. This footprint variant is used primarily as a benchmark since cities worldwide are assigned equal ED values per capita. The Global Average Footprint variant is calculated as follows:

(5)

$$FF_{ga} = (ED_{gtot} + FL)\times \frac{Pop_{city}}{Pop_{global}} \times \frac{Exp_{nat}}{Exp_{global}}$$

Where FF_{ga} represents the Global Average Footprint calculated at a national level irrespective of how much of each commodity is consumed in each city or country; FL represents Other Forest Loss; and ED_{gtot} represents the sum of ED attributed to all commodities. Exp_{nat} represents average national household expenditure given in constant 2010 US dollars taken from the World Bank (2021b), and Exp_{global} represents the average global national household expenditure from the same source (see Table 5 for the units associated with each variable).

5.2 The Distributed Impact Footprint

The Distributed Impact Footprint considers differences in consumption among cities while still assuming equal distribution of deforestation impacts regardless of country of production. The following equations are used to calculate the Distributed Impact Footprint variant at the national, urban, and city level, in that order:

(6)

$$FF_{din} = (\sum_{com} (FI_{gcom} \times C_{napp}) + FL)\times \frac{Pop_{city}}{Pop_{nat}}$$

Where FF_{din} represents the Distributed Impact Footprint calculated at the national level, and Σ_{com} represents the sum of ED consumed across all commodities. This is given by multiplying Forest Impact Factor (FI_{gcom}) of a given commodity by the national apparent consumption (C_{napp}) of the same commodity. Other Forest Loss (FL) is added to the total (Σ_{com}) and scaled from national (Pop_{nat}) to city population (Pop_{city}).

(7)

$$FF_{diu} = ((\sum_{com} (FI_{gcom} \times C_{napp})\times EF_{urb}) + FL)\times \frac{Pop_{city}}{Pop_{nat}}$$

Where FF_{diu} represents the Distributed Impact Footprint calculated at the urban level, and Σ_{com} represents the sum of ED consumed across all commodities. This is given by multiplying the Forest Impact Factor of a given commodity (FI_{gcom}) by the national apparent consumption (C_{napp}) of the same commodity and the Urban Expenditure Factor (EF_{urb}). Other Forest Loss (FL) is added to the total (Σ_{com}) and scaled from national (Pop_{nat}) to city population (Pop_{city}).

(8)

$$FF_{dic} = \begin{cases} (\sum_{com} (FI_{gcom} \times C_{com}) + FL)\times \frac{Pop_{city}}{Pop_{nat}} & \text{if } C_{com} \text{ is available} \\ (\sum_{com} (FI_{gcom} \times C_{napp} \times CR_{com}) + FL_{other})\times \frac{Pop_{city}}{Pop_{nat}} & \text{otherwise} \end{cases}$$

Where FFdic represents the Distributed Impact Footprint calculated at the city level, and ∑com represents the sum of ED consumed across all commodities. This is given by multiplying the Forest Impact Factor of a given commodity (FIgcom) by either the subnational direct consumption (Ccom) of the same commodity—if available—or the national apparent consumption (Cnapp) and the Commodity-Specific Consumption Ratio (CRcom) of the same commodity. In both cases, Other Forest Loss (FL) is added to the sum before scaling from the national (Popnat) to city level (Popcity).

5.3 The Trade Flow Footprint

Finally, the Trade Flow Footprint traces deforestation attributed to commodities from their country of production to the country where they are consumed. Whereas the second Distributed Impact variant allows for the indirect effects of consumption on deforestation (e.g., increased demand for soybeans in the U.S. incentivizing deforestation for soy farms in Brazil), the third Trade Flow variant includes only the direct effects of consumption on deforestation (e.g., thus consumption of Brazilian-grown soy carries ED and Canadian-grown soy does not). The Trade Flow Footprint variant calculations at the national and city levels are given by the following equations:

(9)

$$FF_{tfn} = (\sum_{com} ED_{pcom} + FL)\times \frac{Pop_{city}}{Pop_{nat}}$$

Where FFtfn represents the Trade Flow Footprint calculated at a national level, and ∑com represents the sum of ED consumed across all commodities. This is given by the ED consumed at a national level for each commodity (EDpcom)—as calculated by the Physical Trade Model—and Other Forest Loss (FL) before scaling from the national (Popnat) to city level (Popcity).

(10)

$$FF_{tfu} = (\sum_{com} ED_{pcom} \times EF_{urb} + FL)\times \frac{Pop_{city}}{Pop_{nat}}$$

Where FF_{tfu} represents the Trade Flow Footprint calculated at an urban level indifferent to commodity-specific consumption, and $\sum_{com}$ represents the sum of ED consumed across all commodities. This is given by multiplying the embodied deforestation consumed at a national level (ED_{pcom})—as calculated by the Physical Trade Model—by the Urban Expenditure Ratio (EF_{urb}), and FL represents Other Forest Loss before scaling from the national (Pop_{nat}) to city level (Pop_{city}).

(11)

$$FF_{tfc} = (\sum_{com} (ED_{pcom} \times CR_{com}) + FL)\times \frac{Pop_{city}}{Pop_{nat}}$$

Where FFtfc represents the Trade Flow Footprint calculated at a city level, and ∑com represents the sum of ED consumed across all commodities. This is given by multiplying the embodied deforestation consumed at a national level (EDpcom)—as calculated by the Physical Trade Model—by the Commodity-Specific Consumption Ratio (CRcom). Other Forest Loss (FL) is added before scaling from the national (Popnat) to city level (Popcity).

Table 5 | **Units Associated with Variables Used in Footprint Variant Calculations**

VARIABLE	SHORTFORM	UNIT
Global Average Footprint	FF_{ga}	Hectares (ha)
Distributed Impact Footprint (national, urban, city)	FF_{din} FF_{diu} FF_{dic}	
Trade Flow Footprint (national, urban, city)	FF_{tfn} FF_{tfu} FF_{tfc}	
Other Forest Loss	FL	
Embodied deforestation consumed at a national level	ED_{pcom}	
Forest Impact Factor	FI_{gcom}	Hectares per tonne (ha/t)
Subnational direct consumption	C_{com}	Tonnes
National apparent consumption	C_{napp}	
Population (national, city)	Pop_{nat} Pop_{city}	Persons
Urban Expenditure Ratio	EF_{urb}	none
Commodity-Specific Consumption Ratio	CR_{com}	

Source: Authors

6. CALCULATING CO_2 EMISSIONS FROM CONSUMPTION OF EMBODIED DEFORESTATION

The final step of the Forest Footprint is calculating CO_2 emissions from consumption of land-based products. This is given in two different metrics: CO_2 emissions from consumption of recent tropical and subtropical ED and carbon opportunity costs (COC). The former represents CO_2 emissions from loss of aboveground and belowground biomass due to deforestation, whereas the latter represents the total historical amount of land-based carbon lost from vegetation and soils on productive agricultural lands for a given commodity (this quantity also represents the amount of carbon that could be stored if land in production were allowed to return to native vegetation). Both metrics are presented within the Forest Footprint to understand the relationship between CO_2 emissions from the consumption of ED and the larger, historical emissions of land-use conversion for agriculture; however, currently only the former is directly compatible with cities' GHG accounting methods (WRI et al. 2022).

The Forest Footprint uses deforestation emissions data from Pendrill et al. (2019b, 2020), given in tCO_2/ha. Pendrill et al. (2019b, 2020) give CO_2 emissions linked to ED as a single sum without a range or standard error. We contend that the single figure is appropriate in strongly communicating the measure of deforestation risk in terms that cities can relate to (see Table 7 and Section 7.3 for further discussion). It should, however, be acknowledged that emissions calculated from land-use change models are uncertain (Bontinck et al. 2020). This is largely due to the fact that tropical and subtropical forest carbon stocks themselves are difficult to ascertain (Ramankutty et al. 2006; Pan et al. 2011). The deforestation emissions for the Global Average, Distributed Impact, and Trade Flow Footprint variants (respectively, DE_{ga}, DE_{di} and DE_{tf}) are calculated according to:

(12) $$DE_{ga} = FF_{ga} \times \frac{DE_{tot}}{t}$$

(13) $$DE_{di} = FF_{di} \times \frac{DE_{tot}}{t}$$

(14) $$DE_{tf} = \sum_{com} DE_{com} \times \frac{Pop_{city}}{Pop_{nat}}$$

Where DE_{com} represents the total emissions from deforestation given by Pendrill et al. (2020), and t represents the number of years where deforestation has been assessed by Pendrill et al. (2020). The deforestation emissions for the Trade Flow Footprint variant (DE_{tf}) are calculated differently; the Physical Trade Model (Pendrill et al. 2020) traces deforestation emissions from the source country of deforestation to the country of final consumption. Thus, Σ_{com} represents the sum of deforestation emissions for each commodity (DE_{com}) consumed by the country in which the city is located. These calculations are to be performed with data from the closest level of geographic scope available (i.e., city level).

Carbon opportunity costs (COC) represent the total historical amount of land-based carbon lost from vegetation and soils on agricultural lands (Searchinger et al. 2018; Waite et al. 2019). COC factors for commodities are obtained by dividing the time-discounted annual rate of total historical carbon losses on lands producing a given commodity (e.g., beef, soy, etc.) by the total annual production of that commodity. The concept of time discounting means that CO_2 is attributed to the production of crops at a discounted (i.e., decreasing) yearly rate starting from the initial land-use conversion event. This metric considers carbon losses in both tropical and temperate ecosystems. Because carbon losses occur quickly but lands can be productively used for many years, the COC is annualized using a discount rate of 4 percent that effectively distributes the carbon losses from land conversion over 30–35 years. COC per kilogram of a commodity can also be thought of as the amount of carbon likely to be lost from plants and soils as a result of producing an additional kilogram of that food. COC is presented in tandem with GHG emissions from recent deforestation as a means of

Table 6 | **Categorical Connection of Carbon Opportunity Cost Factors to Forest Footprint Commodities**

COMMODITY	COMMODITY SUBCATEGORY	ASSOCIATED COC CATEGORY	CARBON OPPORTUNITY COST FACTOR (KG CO_2E/KG FRESH WEIGHT)
Soy	Food	Soybeans/Tofu	5.85
	Feed	Soy meal	4.92
	Fuel	Soybeans (oil)	9.98
Palm Oil	Food	Palm (oil)	8.26
	Fuel	Palm (oil)	8.26
Beef	Food	Beef and buffalo meat	143.92
Wood Fiber	Wood	n/a	
	Wood fuel		
	Paper		
Hotspot Crops	Cocoa	Cocoa	40.36
	Rubber	n/a	
	Coffee	Coffee	31.13
	Tobacco	Stimulants and spices misc.	44.63
	Spices	Stimulants and spices misc.	44.63
	Sugar	Sugars and sweeteners	1.75
Other Crops	Tree nuts	Tree nuts and seeds	7.59
	Pulses	Beans and pulses (dried)	10.53
	Fiber crops	Seed cotton	2.86
	Oilseeds nec	Vegetable oils	4.79
	Rice	Rice	2.61
	Other cereals	Grains/cereals (except rice)	2.02
	Roots and tubers	Roots and Tubers	1.12
	Fruits	Fruits	1.03
	Vegetables	Vegetables	0.71

Sources: Authors and Waite et al. 2019.

showing the more general CO_2 impacts of the consumption of food products, rather than just impacts on tropical forests. COC is calculated as:

(15)

$$COC_{din} = \sum_{com} (COC_{com} \times C_{napp}) \times \frac{Pop_{city}}{Pop_{nat}}$$

Where COC_{com} represents the commodity-specific carbon opportunity cost factor (given in tCO_2 per tonne of commodity—see Table 6) and COC_{din} represents the total carbon opportunity cost calculated for the Distributed Impact Footprint variant at the national level. This equation is representative of similar COC calculations, which can also be done with equations 5–8 for the Global Average and Trade Flow Footprint variants by replacing FI_{gcom} with COC_{com}.

Because the deforestation emission factors from Pendrill et al. (2020) consider emissions from recent tropical and subtropical deforestation attributed to all the aforementioned commodities, and the COC considers emissions linked to historical land-use change across only food-based agricultural commodities, COC estimates are higher. For instance, the COC factor per kilogram of coffee is almost 400 times larger than the emission factor from recent coffee-related deforestation, while the COC factor is about 10 times higher per kilogram of beef and soy and 1.5 times higher per kilogram of palm oil, versus the respective emission factors from recent deforestation. As Pendrill et al. (2020) do not currently provide data on weights of commodities consumed through the Physical Trade Model, only the Global Average and Distributed Impact Footprints are able to be converted to COC. It is also important to note that COC estimates of wood and rubber products have yet to be developed and the consumption of wood fiber and rubber is therefore excluded from the COC estimates.

7. COMPARISONS, ASSUMPTIONS, AND LIMITATIONS

The Forest Footprint methodology relies on assumptions that must necessarily be made due to a lack of specific data and/or for ease of comparability between cities. These assumptions are categorized by attribution, consumption, and deforestation (Sections 7.1–7.3) and represent limitations (Section 7.4) in the accuracy of the Forest Footprint methodology. Some of these limitations are inherent in the data sets we have selected, while others arise from assumptions specific to our methods, which we intend to address in future iterations of this methodology.

7.1 Comparison of Attribution Methods and Assumptions

As discussed in Section 4, Pendrill et al. (2020) rely on FAO land-use data to calculate amounts of ED. Deforestation attribution data have also been estimated via remote sensing from satellite imagery based on Hansen et al. (2013). A study by Curtis et al. (2018) estimated global drivers of deforestation using a forest loss classification decision-tree model via remote sensing. This improved upon the Hansen et al. (2013) data set, which estimated only tree cover loss and not deforestation.[8] While this method is positioned to overcome many of the limitations of Pendrill et al.'s (2020) LanBaDA method, it is not used in the Forest Footprint calculations because it was developed at a resolution (10-km cells) that is too coarse for this methodology.[9]

Goldman et al. (2020) have further built upon the Hansen data by comparing spatially explicit GIS agricultural land-use data sets against Hansen et al.'s (2013) forest-cover-loss data to estimate "agriculture-linked deforestation." The study analyzes many of the same commodities as Pendrill et al. (2019a, 2019b, 2020), but the results from Goldman's and Pendrill's studies differ in important ways. Beyond the obvious methodological differences, Goldman et al. attribute discrepancies to their more fine-grained categorization of land uses, which, in turn, led to differences in ED estimates. For instance, Goldman et al. (2020) consider only cuts from forest plantations labeled as "wood fiber" from Harris et al. (2019) to be deforestation, whereas Pendrill et al. (2019, 2020) consider cuts from all forest plantations to be deforestation. ED from wood fiber, therefore, differed by a factor of four between the two studies.

For the purposes of attributing ED in this model, we chose to use Pendrill et al. (2019a, 2020). Because the Forest Footprint's main goal is to raise awareness around ED consumed in cities, our model benefits less from the detailed subnational and spatially explicit ED data provided by Goldman et al. 2020 than from a smaller set of assumptions covering a wide range of commodities that can be more quickly understood by a broader, non-specialist audience.

7.2 City Consumption Assumptions

All footprint calculations assume an average resident profile for each city being footprinted. While there are large discrepancies in individual consumption behavior (depending both on a resident's socioeconomic situation and personal choices), we again opted to provide an easily communicable and relatable snapshot of the impacts of city dwellers on tropical and subtropical deforestation.

As for the product categories used to calculate consumption ratios, it is assumed that within a given country there is no difference between products consumed in urban, non-urban, and city areas (e.g., average cocoa content in chocolate). Additionally, in certain cases, these commodity-specific consumption ratios may include items that do not contain any of the identified commodity (e.g., using vegetable oils taken from a household consumption survey to calculate the city-level consumption ratio of palm oil). As it is difficult to ascertain the consumption shares of commodities within all product categories (e.g., how much palm oil is used per kg of chocolate or soap), it is assumed that any difference in consumption of product categories (e.g., from national- to city-level consumption of vegetable oils) is directly proportional among all commodities within the product category. For example, while per capita vegetable oil consumption in country X might be higher than city Y (within country X), without knowing the contents of vegetable oil or the types of oil included in the survey it is impossible to estimate how much less palm, sunflower, or olive oil residents of city X consume compared to citizens of country Y.

Many of the data sets used for commodity-specific consumption data are based on different years (e.g., 2015 timber consumption and 2011 fuelwood consumption), whereas the forest impact factors are based on average deforestation linked to agricultural production over the 2005–17 period. No adjustments have been made to correct for the differences in consumption data by year; thus, it is assumed that consumption levels have neither increased nor decreased substantially since the data were published.

7.3 Deforestation Attribution Assumptions

Other Forest Loss assumes that forest loss (including deforestation) due to wildfires, forestry outside of plantation forests, shifting agriculture, and urbanization can be attributed to human actions and are thus equally the responsibility of people worldwide, who should take mitigating action regardless of their location or consumption patterns.

Estimates of GHG emissions from recent deforestation and forest loss vary widely. This is due to many factors, including geographical scope and other methodological differences. The

Table 7 | **Comparison of Estimated Emissions from Tropical and Subtropical Deforestation**

STUDY	EMISSIONS FROM DEFORESTATION (PG C/YR[a])	TIME PERIOD	DEFORESTATION (MHA/YR[b])	GEOGRAPHICAL SCOPE	GHG EMISSIONS PER HA OF DEFORESTATION (TCO_2/HA)
Le Quéré et al. 2009. "Trends in the Sources and Sinks of Carbon Dioxide."	1.5 ± 0.7	1990—2005	8.351[c]	Global	659 ± 307
Pan et al. 2011. "A Large and Persistent Carbon Sink in the World's Forests."	1.30 ± 0.47 (net)	1990—2007	8.546[d]	Tropical and subtropical	558 ± 301
Baccini et al. 2012. "Estimated Carbon Dioxide Emissions from Tropical Deforestation Improved by Carbon-Density Maps."[e]	1.14 (gross)	2000—10	7.933 ± 0.817[f]	Dry and humid tropical	527 ± 48.9
Pendrill et al. 2020. "Deforestation Risk Embodied in Production and Consumption of Agricultural and Forestry Commodities 2005-2017."[e]	0.71 (net)	2005—17	4.974	Tropical and subtropical	519
Achard et al. 2014. "Determination of Tropical Deforestation Rates and Related Carbon Losses from 1990 to 2010."[e]	0.88 ± 0.36 (gross)[g]	2000—10	7.62 ± 0.33	Tropical	423 ± 292

Notes:

a Pg C/yr = Petagrams carbon per year. [b] Mha/yr = million hectares per year. [c] Le Quéré et al. (2009) take net global changes in forest from FAOSTAT's Global Forest Resources Assessment (FAO 2005). [d] Pan et al. (2011) take net tropical and subtropical changes in forest area from FAOSTAT's Forest Resources Assessment (FAO and JRC 2010). [e] Study uses carbon-density maps. [f] For years 2000–05, Baccini et al. (2012) take tropical forest loss data from Hansen, et al. (2010). [g] This range is based on minimum and maximum carbon density from Saatchi et al. (2011).

Source: Authors.

Forest Footprint and Pendrill et al. (2019b, 2020) focus on gross emissions from deforestation, whereas many other studies expand this scope to include forest degradation and reforestation (Seymour and Busch 2016, 41). Of the other studies that focused on deforestation and not degradation, Pan et al. (2011) was the only one able to determine net deforestation, whereas Baccini et al. (2012) and Achard et al. (2014) measured remote-sensed forest loss. While Le Quéré et al. (2009) used land-use data to estimate emissions, the study does not disaggregate emissions from land-use change (for 2005–10, the study uses forest fire emissions as a proxy for emissions from deforestation) and does not distinguish deforestation by forest biome. As evident in Table 7, Pendrill et al.'s (2020) estimate of GHG emissions per hectare of deforestation lies within the ranges given by these studies.

7.4 Other Limitations

Many products are not fully captured within the footprint. In cases where countries import highly processed products of commodities (e.g., frozen pizzas), all footprint calculations may be underestimates due to the difficulties of calculating consumption of commodities embedded in categories of imported products. In other cases, commodities cannot be fully identified; for example, UN COMTRADE groups both real and imitation leather products together in its trade data. A different kind of problem exists in that no footprint calculation accounts for the impact of activities with little direct economic measure, such as subsistence farming and wood harvesting, which are nevertheless relevant to the consumption of products.

In addition, the Forest Footprint does not fully capture carbon opportunity costs related to animal products beyond beef (i.e., lamb, pork, poultry, eggs, and dairy products) as it captures only the carbon opportunity costs associated with soy-based animal feeds but not those costs associated with cropland or pastureland use beyond beef and soy production. It also does not capture carbon opportunity costs related to rubber or wood production.

There are many more effects of land-use change outside of the Forest Footprint that should be accounted for in promoting changes in consumption from one commodity to another (e.g., conversion of grasslands and degraded soil health). For instance, while palm oil is a major driver of tropical and subtropical deforestation, it has one of the highest yields (in tonnes per hectare) of all oilseeds. Thus, while switching vegetable oil or biofuel consumption to a different oilseed may result in a lower Forest Footprint it may result in other adverse effects such as increased or intensified agricultural land use in other environments, which may, in turn, lead to more deforestation than using palm oil.

It is known that UN trade and production data (COMTRADE and FAOSTAT) present some inaccuracies in estimating apparent consumption at the national level—most notably in commodity misinvoicing in developing countries (Ndikumana 2016). Misreporting of trade volume is a well-known strategy used by transnational companies to avoid export tariffs on primary commodities; however, this is most common with high-value, low-weight products and goods without standard international pricing regimes. For example, the recent UNCTAD report (Ndikumana 2016) identified cocoa from Côte d'Ivoire as a leading example of large-scale under-invoicing, along with Chilean copper, Nigerian oil, and South African gold. This means that commodity trade data may sometimes be underreported. On the production side, this phenomenon has been accounted for in certain cases by incorporating other comparably reliable sources of production data, such as U.S. Foreign Agriculture Service data; however, due to the number of commodities and their products assessed, the correction is often limited to outliers. Both discrepancies affect apparent consumption estimates and render the Distributed Impact Footprint estimate marginally higher than it might otherwise be.

The commodity-specific consumption data rely heavily on household survey data. While these data sets are widely available for most countries, they present some limitations and vary in their ability to capture current trends in commodity consumption (FAO and World Bank 2018). Survey methods may not adequately represent all consumption pathways, such as food that is acquired but not purchased and food that is consumed away from home (for instance, food consumed in restaurants is not accounted for). These considerations are especially important in developing countries where consumption patterns are rapidly changing. In addition, household survey data often report total household expenditure (in local currency, USD, or PPP), and geographically specific differences in commodity prices (such as rural and urban beef prices) are difficult to account for due to data availability and quality.

The use of household surveys also excludes the measure of city-specific consumption of private businesses. While this may be a significant factor (and is accounted for nationally), it is difficult to attribute the consumption or waste of private businesses to cities as it would be necessary to know whether the businesses' products were being finally consumed within the city or not. For commodities such as wood fiber, economic census data can be used, which includes households, private corporations, and public institutions.

7.5 Summary

The Forest Footprint can help cities understand their impact on tropical and subtropical deforestation by presenting consumption data in an accessible manner. As the impacts of decisions made by city or metropolitan jurisdictions on tropical and subtropical forests are difficult to see, the Forest Footprint brings these impacts into the visible realm and sets the stage for further incorporation of consumption-based emissions and impacts in city governance and sustainability planning. By understanding their forest footprints, cities worldwide can join the growing number of private sector and national government actors who are reducing tropical and subtropical deforestation as they measure, monitor, and ultimately transform the infrastructure and the culture of urban consumption.

ENDNOTES

1. The guidance can be found here: https://ghgprotocol.org/gpc-supplemental-guidance-forests-and-trees.

2. At the time of writing, it is not required by the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) standards to include GHG emissions from consumption of products that embody deforestation linked to agricultural production—let alone any extraterritorial consumption-based emissions—within either the GPC BASIC or BASIC+ schemes (WRI, C40, and ICLEI 2021). We use the term "consumed embodied deforestation" as shorthand for "consumption of products whose production is associated with the loss of forest cover in tropical or subtropical zones" thus, deforestation is embodied in these products.

3. Curtis et al. (2018) attribute 0 and 1 percent of forest cover loss between 2001 and 2015 to permanent deforestation in Europe and North America, respectively. When portions of boreal or temperate forests are cleared for timber, they are almost always allowed to grow back, whether they are replanted or allowed to regenerate naturally. While this can have negative biodiversity and carbon impacts in boreal and temperate regions, these impacts are not as acute or as well understood as those of tropical and subtropical forests. City staff should be aware of these issues when choosing which building materials to promote (or procure) within the city. For all commodities apart from wood and rubber, temperate and boreal deforestation is indirectly represented in the carbon opportunity cost metric (see Section 6), which factors the global climate impact of dedicating land to production of the given commodity.

4. In certain cases where climate planning is carried out primarily at the metropolitan level (i.e., comprising multiple municipalities), a metropolitan footprint may prove to be more appropriate and must reflect not only the metropolitan population but also metropolitan consumption data.

5. The data set can be found here: https://www.naturalearthdata.com/downloads/110m-cultural-vectors/110m-populated-places/.

6. While GPC land sector guidance protocol (WRI 2022) is to use a 20-year amortization period for calculating emissions from land use changes, Pendrill et al. (2019a, 2019b, 2020) use a five-year amortization period for two main reasons. Firstly, the study is constrained by available data on tree cover loss to the period 2001–14. Thus, only 1-, 5-, and 10-year amortization periods were able to be compared. Differences between these periods were found to be negligible.

7. There are a few reasons why Pendrill et al. (2019a, 2019b, 2020) have omitted highly processed products from their analysis, the most salient of which is that Kastner et al. (2014a), on which Pendrill's report is based, focus on the trade of agricultural commodities irrespective of the differences of impact (i.e., deforestation) per country and region. Kastner et al. give the example of China's trade in cotton-based clothing. Because clothing is relatively equal in terms of imports and exports there is no need to track these types of products to estimate national consumption of cotton. Other factors such as the high degree of variation in the use of primary commodities in highly processed products (e.g., types of oils used in soaps) make tracking products using international trade data all the more difficult.

8. See also Leblois et al. (2017), Ordoway et al. (2017), and the ongoing work of Global Forest Watch (https://www.globalforestwatch.org/) and geo-Footprint (https://geofootprint.com/) for other examples of ED estimation via remote sensing.

9. Another method worth noting was developed by 3Keel Consultants in their 2017 study of the UK's national deforestation impact (WWF-UK and RSBP). They developed a "deforestation risk factor" on a scale of 1 to 12 for each commodity and source.

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ABBREVIATIONS

COC	Carbon opportunity costs
COICOP	Classification of Individual Consumption by Purpose
ED	Embodied deforestation
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic information system
GHG	Greenhouse gas

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.