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Life cycle assessment synthesis of the carbon footprint of Arabica coffee: Case study of Brazil and Vietnam conventional and sustainable coffee production and export to the United Kingdom

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Over 9.5 billion kg of coffee is produced annually and demand is expected to triple by 2050. Hence, the identification and quantification of the greenhouse gas emission footprint of coffee is essential if it is to become a more sustainable crop. We have produced a detailed life cycle assessment of the carbon equivalent footprint of coffee produced in Brazil and Vietnam and exported to the United Kingdom. The average carbon footprint of Arabica coffee from both countries was calculated as 15.33 ($\pm$0.72) kg of carbon dioxide equivalent per 1 kg of green coffee (kg CO_{2e} kg^{-1}) for conventional coffee production and 3.51 ($\pm$0.13) kg CO_{2e} kg^{-1} for sustainable coffee production. The 77% reduction in carbon footprint for sustainable coffee production in comparison to conventional production was due to exportation of coffee beans via cargo ship rather than freight flight and the reduction of agrochemical inputs. Based on our results, further reductions could be made through optimal use of agrochemicals; reduced packaging; more efficient water heating; renewable energy use; roasting beans before exportation; and carbon offsetting. Applying these recommendations correctly through certification schemes could mitigate other environmental impacts of coffee cultivation.

1 | INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 2019) warned that humans have damaged a quarter of land on Earth (2 billion hectares) through land degradation and agriculture, which are responsible for almost a quarter of the world's greenhouse gas (GHG) emissions. The IPCC (2018) report suggests that global emissions must halve by 2030 and be net zero by 2050 if global temperature rise is to be kept to 1.5°C. Agriculture will play an important role in managing the land and reducing GHG gas emissions.

Coffee is a luxury agricultural commodity, sometimes referred to as a "drug food," as it provides no nutritional value. In 2018, coffee was the World's 121st most traded product, representing 0.17% of total world trade (OEC). Between 2017 and 2018 coffee exports grew by 1.49%. Coffee is the world's 70th most traded agricultural commodity (International Coffee Organization [ICO], 2019), with over 9.5 billion kg produced in 2018 (Figure 1) with a total trade value of $30.9 billion (OEC). Coffee is grown in tropical regions where the ecosystems are considered fragile due to other human pressures.

Coffee cultivation can play a crucial role in maintaining and providing ecosystem services at a local and national level and has a substantial role to play in mitigating the agricultural sector's environmental impact. With demand for coffee expected to triple by 2050 (Conservation International, 2019b), the increasing global demand for environmentally friendly products has pushed a rapid acceleration of sustainability initiatives among coffee producers and retailers (Noponen, 2012).

If coffee is to become more sustainable we need to understand how and where GHGs are emitted through the production cycle and whether mitigating these emissions will increase or decrease the environmental impact of coffee cultivation. To this end we have applied an entire life cycle carbon footprint analysis (Cheng et al., 2014). This approach has previously been used in agriculture (Ponsioen & Blonk, 2012), food consumption (Shirley et al., 2012), industrial production (Virtanen et al., 2011), and international trading (Peters et al., 2011). Analyses for individual agricultural products have been carried out, including butter (Flysjö, 2011), dairy (Asselin-Balençon et al., 2013), honey (Mujica et al., 2016), sugar (Yuttitham et al., 2011), wine (Pattara et al., 2012), and coffee products in Japan (Hassard et al., 2014). A carbon footprint analysis by Hertwich and Peters (2009) concluded that global food production and consumption is the source of 20% of total anthropogenic GHG emissions, the majority of which is linked to agriculture (Cheng et al., 2014).

2 | COFFEE CULTIVATION

Most coffee grown is made up of two species: *Coffea arabica* (Arabica) and *Coffea canephora* var. Robusta (Robusta), the former making up 70% of all coffee grown globally, and the latter encompassing the remaining 30% (ICO, 2019). Globally, coffee is currently grown between 22°N and 26°S (Wintgens, 2008). Germination of a coffee seed takes one to two months (Wintgens, 2008) and the plant takes approximately three years to mature and begin producing fruit (Hoffmann, 2018). The coffee plant flowers for less than two weeks, which is followed by the development of the coffee cherries. Development takes 6–9 months for Arabica and 9–11 months for Robusta (Wintgens, 2008). At this stage, the berries turn from green to deep red and are ready for harvesting. Cultivated coffee trees have a lifespan of around 30 years (Bunn et al., 2015). Though they can live up to 80 years in the wild, the most productive years are between 7 and 20 years.

Arabica coffee originated in Ethiopia and is grown within tropical forests at altitudes of 1,600–2,800 m (DaMatta, 2004). This region has well distributed rainfall patterns, ranging from 1,400 to 2,000 mm for two thirds of the year, with the last third being the dry season and coinciding with the coldest months (Haggar & Schepp, 2012). Arabica's optimum rainfall is between 1,200 and 1,800 mm annually, and below 1,000 mm coffee plants cannot survive. The species prefers
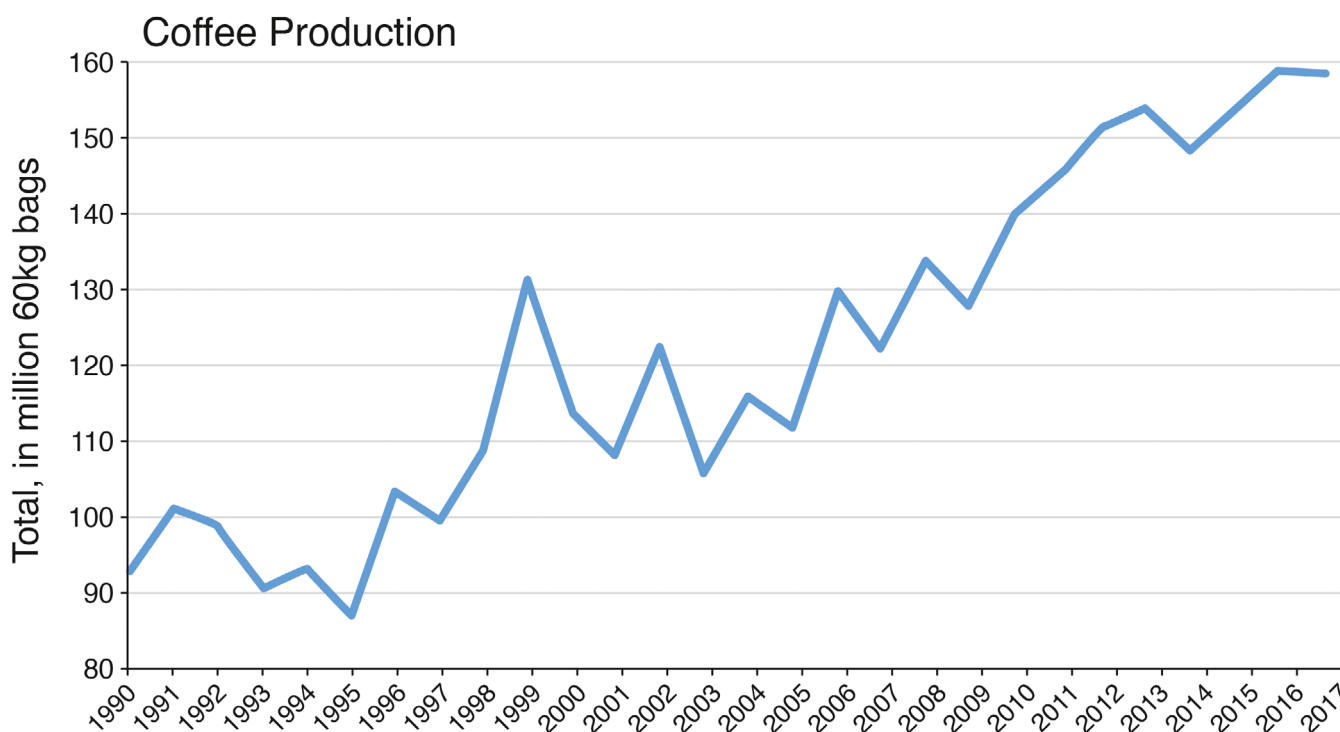

FIGURE 1 Total production of coffee by all exporting countries, 1990–2018 (data from ICO, 2019).

temperatures between 18 and 22°C with little seasonal fluctuations (de Camargo, 2010), though it can tolerate temperatures as low as 15°C and up to 25°C (Wintgens, 2008). These stringent environmental requirements mean that Arabica is mostly grown in regions around the equator, with the major production areas being the Brazilian highlands, Central America, and Colombia (Hoffmann, 2018). There are major concerns that future climate change (DaMatta et al., 2019) will greatly reduce the areas suitable for coffee cultivation, mainly due to the increased seasonal temperatures; see Bunn et al. (2015) for a comprehensive review.

3 | COFFEE PRODUCTION

This study focuses on two sites in Brazil and Vietnam, and evaluates the different processes involved in the supply chain of Arabica coffee exported to the United Kingdom. Brazil and Vietnam were chosen as they are the two largest coffee producing countries, together producing over 50% of the world's Arabica coffee (Figure 2). Brazil is the world's largest producer of coffee beans, responsible for around 30% market share. Since 2008, coffee production in Brazil and Vietnam has increased by 60% and 165% on average, respectively, in comparison to average 1990–2007 levels. In the 2017/2018 season, Brazil produced over 3 million metric tons of coffee (51 million bags), of which 60% was exported, whilst Vietnam produced 1.8 million metric tons of coffee (30 million bags), of which approximately 80% was exported (ICO, 2019).

Coffee's global significance extends beyond its large consumption numbers to the well documented environmental burdens as a result of effluent releases, fertiliser use, and habitat destruction (Hassard et al., 2014). Although there has been substantial research into the environmental impacts of coffee production, it has primarily focused on the production phase and its contribution to the displacement of natural habitats and communities (e.g., Komar, 2006; Rappole et al., 2003). Significantly less consideration has been given to the environmental cost of coffee processing, including the transportation from the production to consumption countries.

Conventional coffee production consumes substantial amounts of energy, water, and land, which can have potentially significant impacts on native tropical biodiversity (Arce et al., 2009), particularly due to the long, complex supply chain required to produce and transport the coffee bean to market. Although only grown in tropical and equatorial areas as the
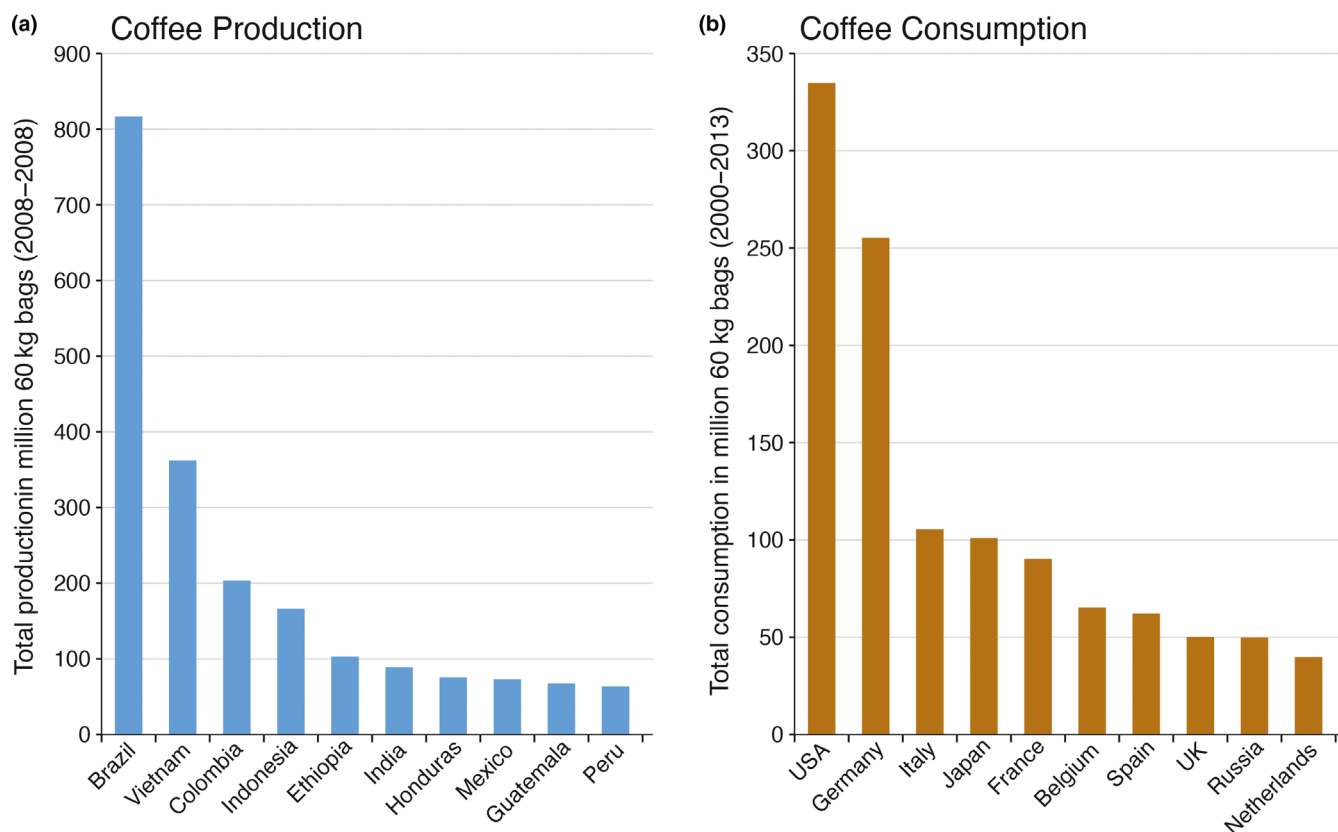

FIGURE 2 (a) Global top 10 coffee producers, 2000–2018; (b) global top 10 coffee consumers, 2000–2013 (data from ICO, 2019).

primary export of many developing countries, the majority of coffee consumption occurs in the developed world, with the European Union (EU) and the United States importing two-thirds of coffee produced worldwide (Salomone, 2003); see Figure 2. The significant distance from production to final destination means there is a large amount of carbon emissions associated with the transportation phase alone, with roughly 15% of GHG emissions in coffee's lifecycle attributed to international transportation (Humbert et al., 2009; Killian et al., 2013; PCF Pilotprojekt Deutschland, 2008).

4 | COFFEE CERTIFICATION AND SUSTAINABILITY SCHEMES

With mounting global focus on climate change, an increasing number of coffee associations and individual companies are introducing sustainability schemes. In 2015, Starbucks announced that it had reached an industry milestone of 99% ethically sourced coffee (Starbucks Coffee Company, 2019) and launched a traceability pilot programme, The Sustainable Coffee Challenge. The programme aims to make coffee the world's first fully sustainable agricultural product and has since grown to more than 100 international partners (Conservation International, 2019b). To meet this goal, Nespresso launched the AAA Sustainable Quality Program, which supports more than 45,000 farmers and aims to reduce the carbon footprint of a cup of Nespresso coffee by 28% by 2020 in comparison to 2009 (Nespresso, 2019b). Strategies in the programme range from designing more efficient coffee machines to agroforestry and are informed by life cycle assessments (LCAs). As of 2016, LCAs showed a carbon footprint reduction of 19.4%, with the company "insetting" 100% of its carbon footprint (Nespresso, 2019a); the process of embedding sustainable activities directly into supply chains, instead of offsetting them through indirect carbon-sequestering initiatives.

Over time, the agricultural industry has increasingly used certification as a marketing tool for its products, in response to increased competition and public scrutiny (International Trade Centre [ITC], 2011). These certifications prove to consumers that producers conform to good agricultural practices, practice safe pesticide use, engage in resource protection or protect the environment. As a result, the product is accepted as safe and environmentally friendly. Whilst the certification process is simple for producers of perishables such as a fruit and vegetables, the coffee industry is much more complex as a result of coffee farmers providing green coffee to overseas roasters, who in turn produce and market the finished product. Therefore, the identity of the producing individuals is often not known to the consumer, with the industry's complex supply chain making the validation of practices for certification difficult (Bosselmann, 2012). Nevertheless, several sustainability schemes have been introduced in recent years as a result of the increased consumer demand for environmentally conscious products. In 2012, 40% of global coffee (3.3 million metric tons) was produced in compliance with a voluntary sustainability standard, of which 40% was produced in Brazil and 15% in Vietnam (Potts et al., 2014). With smallholders supplying 70% of the world's coffee (Kolk, 2011), sustainability certification schemes have focused largely on helping coffee farmers maintain their high yield while reducing production costs and environmental degradation, by educating them about optimal fertiliser, energy and water inputs. Additionally, training coffee farmers techniques such as integrated crop management and soil conservation helps them increase soil fertility to reduce the dependence on fertilisers and pesticides, further reducing the inputs required to produce optimal crop quality and quantity. Lower production costs combined with price premiums have been found to make sustainable coffee agriculture more profitable than conventional techniques, whilst maintaining high yields (Gobbi, 2000).

Certification requirements and foci have varied considerably between the five main certification schemes; Fairtrade supports small producers by guaranteeing a price premium, which is meant to be used to enhance social, economic, and environmental development. The Rainforest Alliance and Organic certifications have focused on protecting ecosystems and biodiversity, whilst UTZ aims to mainstream sustainability across the coffee market. In 2011, the ITC conducted an analysis of the effectiveness of the most popular sustainability schemes for coffee, concluding that the Organic and Rainforest Alliance schemes had the biggest environmental impact, particularly in terms of biodiversity and soil fertility. In terms of environmental and sustainability requirements, the Rainforest Alliance certification scheme was found to be the most ambitious.

The certifications have, however, some limitations: many of their criteria are difficult to monitor, such that there is no guarantee certified coffee has been produced according to certification standards. Additionally, the criteria are universal, lacking location-specific requirements for maintaining environmental integrity and biodiversity. In terms of carbon footprint reduction, private schemes such as the Nespresso and Starbucks schemes have been estimated to have a significantly larger impact (Keller e al., 2013) due to their specific focus on reducing GHG emissions, higher level of intervention, and their use of emissions data to inform decisions. Additionally, their specific focus on their own suppliers means that they are able to make more targeted changes in comparison to the blanket standards imposed by the main coffee certification schemes.

5 | LIFE CYCLE ASSESSMENTS

The IPCC (2006), developed a standard inventory methodology for estimating all GHG emissions from the major economic sectors, which is now used by most governments to estimate national GHG emissions (Vergé et al., 2013). The resulting inventories are the foundation of national GHG mitigation strategies and international agreements, yet they are unsuitable for tracking the effectiveness of mitigation strategies as they do not account for the complexity of agroecosystems and the resulting variability between producers, regions, and time. Moreover, the agricultural inventories do not include GHG emissions from energy use, omitting the transportation phase of crop production entirely (IPCC, 1996). As a result, there has been a rapid development of various tools for assessing GHG emissions from agriculture. Some, like Century (Parton et al., 2006), DayCent (Parton et al., 2008), and the US Cropland GHG Calculator (McSwiney et al., 2010), are specifically focused towards assessing the crop production footprint per unit area. Others, such as the Cool Farm Tool (Unilever, 2011) and the Integrated Farm System Model (Rotz et al., 2012), calculate the carbon footprint of a farm as a whole by quantifying each production step. Simpler tools such as the Carbon Calculator (Carbon Farming Group [CFG], 2009) compute footprints per capita or per farm, without accounting for the broad inter-farm practice diversity (Asselin-Balençon et al., 2013). Nevertheless, none of these assessments enable fair comparison per quantity of a certain crop produced, as they do not separate emissions from different crops. The wide-ranging nature of the coffee chain, with many individuals and companies of different types and sizes involved, makes an LCA the most accurate way of quantifying the environmental impact of each stage in coffee production (McGeough et al., 2012; Salomone, 2003).

The LCA method involves mapping out all activities of production, distribution, and consumption of a product, followed by a quantification of all impacts associated with these activities (Figure 3). This method follows the International Organization for Standardization (ISO) 14,000 standards, which define LCAs as comprising four stages: goal and scope definition – outlining what the study intends to assess; inventory – quantifying the life cycle activities and their inflows (resources consumed) and outflows (emissions); impact assessment – mapping these inflows and outflows to measures of environmental damage; and interpretation – evaluating the results and developing recommendations (Kirchain et al., 2017).

5.1 | Life cycle stages of coffee

The life cycle of coffee can be divided into four general stages: production, transportation, roasting, and consumption. The first three stages are generally the same for all types of coffee product, particularly when considering that many companies produce several different coffee products, whereas the final consumption stage processes differ depending on the product type produced.

Although LCAs have been extensively applied to a wide range of agricultural products, their application to coffee is very limited in comparison to other agro-industrial products such as cash crops, dairy products, and canned food (Phrommarat, 2018). Previous LCAs have produced widely varying estimations of the carbon footprint of coffee production, with values ranging from 3.7 to 15.8 kg CO_{2e} kg^{-1} of green coffee (Table 2.2). Studies have collectively agreed that the cultivation and consumption stages have the greatest environmental impact (Arzoumanidis et al., 2017; Coltro et al., 2006; Domínguez-Patiño et al., 2014; Humbert et al., 2009; Killian et al., 2013; PCF Pilotprojekt Deutschland, 2008). PCF Pilotprojekt Deutschland (2008) estimated that 55% of coffee production's carbon footprint was generated during cultivation and on-farm processing and 30% during consumption, with the remaining 15% resulting from transport, processing, and waste disposal. However, to date, all LCAs have been conducted using cargo ships as the method of exportation. Increasingly, roasters are importing fresher coffee, at a much higher price, by shipping the coffee by air instead of ship from the country of origin. These freight flights release an estimated 100 times more CO_{2e} per km travelled than cargo ships (Department for Environment, Food and Rural Affairs [DEFRA] and British Standards Institution [BSI], 2011), making their inclusion in carbon footprint estimations crucial. To date, no LCA has included the exportation of coffee beans via freight flight.

In a carbon footprint analysis of six coffee products, Hassard et al. (2014) calculated the highest impact for the latte (224 g CO_2 per serving), followed by canned coffee (223 g CO_2 per serving), with the lowest impact calculated for espresso coffee (49 g CO_2 per serving). These differences were attributed largely due to differences in packaging and the addition of milk. However, on a per millilitre basis, espresso coffee had the highest impact (1.6 g CO_{2e} ml^{-1}), followed by canned coffee (1.2 g CO_{2e} ml^{-1}), and the latte (0.97 g CO_{2e} ml^{-1}). This indicates the importance of selecting an appropriate functional unit when carrying out LCAs to carry out meaningful comparisons. In this study, the highest contributing factors were the emissions from milk production, packaging, and the production stages of the coffee itself (Hassard et al., 2014).
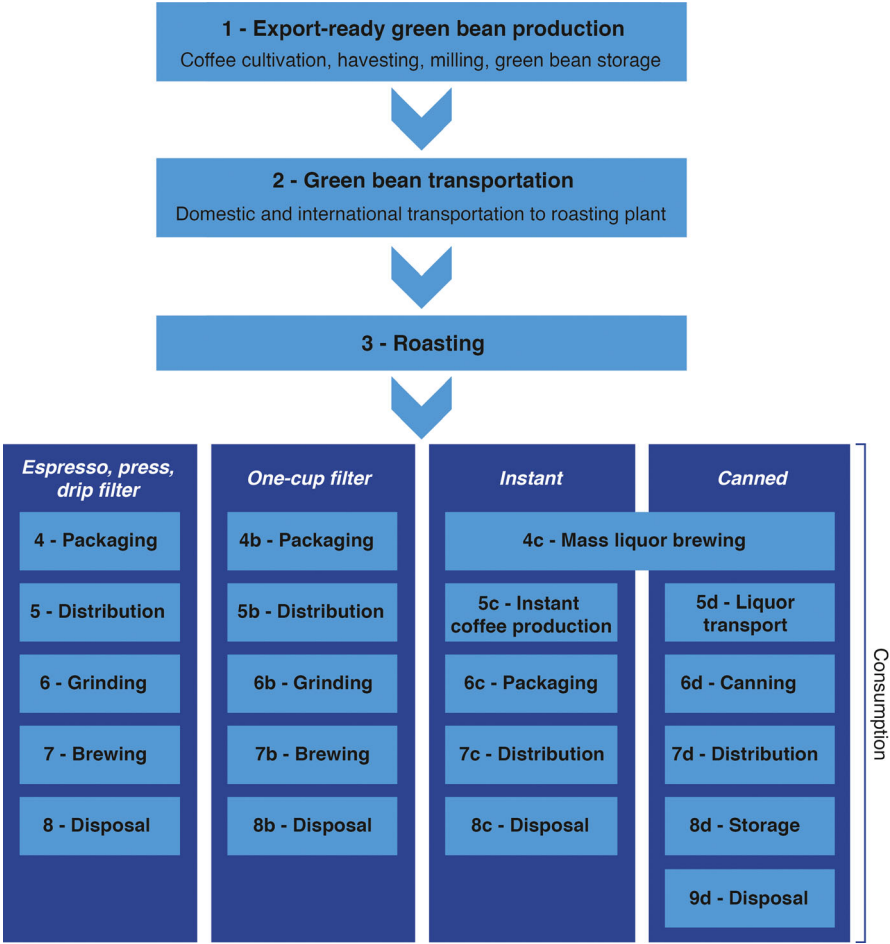
FIGURE 3 General life cycle stages of the production of a serving of coffee (adapted from Hassard et al., 2014).

Indirect, wider environmental impacts are often not considered in carbon footprint assessments due to difficulties in quantifying the amount of carbon they release. For example, an LCA by Salomone (2003) identified eutrophication (320 g $PO_4^{3-}_e$ kg^{-1} of packed coffee) and terrestrial ecotoxicity (6 t/kg of packed coffee) as the main categories of environmental impact from coffee production. This comprehensive assessment included all life cycle stages from coffee cultivation through to consumption and disposal, but omitted fertiliser and pesticide use. In commercial farming, the excessive application of fertilisers (frequency and quantity) has been shown to exceed the soil's ability to retain and transform the nutrients and release them according to the crop's needs (Coltro et al., 2006). Studies have shown that the saturation of the soil with phosphate or nitrogen has promoted losses of phosphates and nitrates into the groundwater (Dubos et al., 2017; Rahman & Zhang, 2018). On a farm level, the use of fertilisers and pesticides can cause the destruction of soil flora and fauna, which can in turn cause both physical and chemical deterioration of the soil itself, the groundwater, and the widespread environment.

Nevertheless, agricultural activities also have positive effects in terms of oxygen generation, carbon capture, and biodiversity protection (Coltro et al., 2006). For example, Pelupessy (2003) estimated that coffee plants capture approximately 35% as much CO_2 as the same area of woodland. None of the studies mentioned in this section considered the potential positive contributions of carbon storage in the coffee ecosystem to climate change mitigation, as carbon footprint estimations only include carbon fluxes between the system and its environment (BSI, 2008). Since coffee production systems can range from simple monoculture plantations to complex agroforests, their above-ground and below-ground carbon stocks vary widely, with estimations ranging from 14.1 Mg/ha in an unshaded coffee monoculture (Hergoualc'h et al., 2012) to 46.3 Mg/ha in a highly diverse agroforest (Soto-Pinto et al., 2010).

To examine the carbon footprint of coffee production, the CO_{2e} emissions from the growing, milling, and exportation phases were first quantified, after which the emissions from the processing phase estimated by a past LCA were investigated.

6 | METHODOLOGY

Coffee's journey from producer to consumer is complex, with multiple sites and companies involved in the supply chain. This makes it difficult to quantify carbon emissions at each life cycle stage, particularly at the farm level where data are scarce. This study covers the full supply chain of Arabica coffee and is based on an extensive collation of secondary data gathered from peer-reviewed academic literature and online databases. The quality and quantity of data available vary depending on which aspect of the LCA is being counted, and this is noted in the methods.

For this study, the coffee supply chain is divided into four separate stages: growing, milling, the process of exportation, and processing (Figure 4a). In order to represent a broader view of carbon emissions across the coffee processing chain, the processing stage is further divided into six smaller stages (Figure 4b), with the information for these stages taken from a previous coffee LCA carried out by PCF Pilotprojekt Deutschland (2008). The scope for this study was defined using PAS 2050:2011, a carbon standard development recommended by the British Department for Environment, Food and Rural Affairs and the British Standards Institution (DEFRA and BSI, 2011).

The calculated carbon footprint must be defined in terms of a functional unit to allow for inter-study comparisons (DEFRA and BSI, 2011). The functional unit defined for this study was 1 kg of green Arabica coffee beans, such that the resulting carbon footprint results are presented as kilograms of carbon dioxide equivalent per 1 kg of green Arabica coffee (kg CO_{2e} kg^{-1} green Arabica coffee beans).

The PAS 2050 method allows for the exclusion of some elements of the carbon footprint in order to simplify the evaluation, stipulating that at least 95% of the total emissions must be assessed. In this study, it is assumed that the land used for coffee production at the selected study sites has been used for this purpose for at least 20 years, such that emissions from land use change and carbon storage by shade trees can be excluded.

(a) Coffee Supply Chain

exportation

growing → milling → land transportation → overseas transportation → land transportation → processing

Brazil/Vietnam | International waters | United Kingdom

(b) Processing stage

roasting → packaging → distribution → grinding → consumption → disposal

(c) Scope of coffee supply chain

growing → milling → exportation → processing

- growing
  - fossil fuels
  - agrochemicals
  - electrical energy
- milling
  - fossil fuels
  - burning of biomass
  - pesticides
  - electrical energy
- exportation
  - fossil fuels
  - land transportation
  - overseas transportation
  - electrical energy
- processing
  - fossil fuels
  - electrical energy
  - land transportation
  - waste/recycling
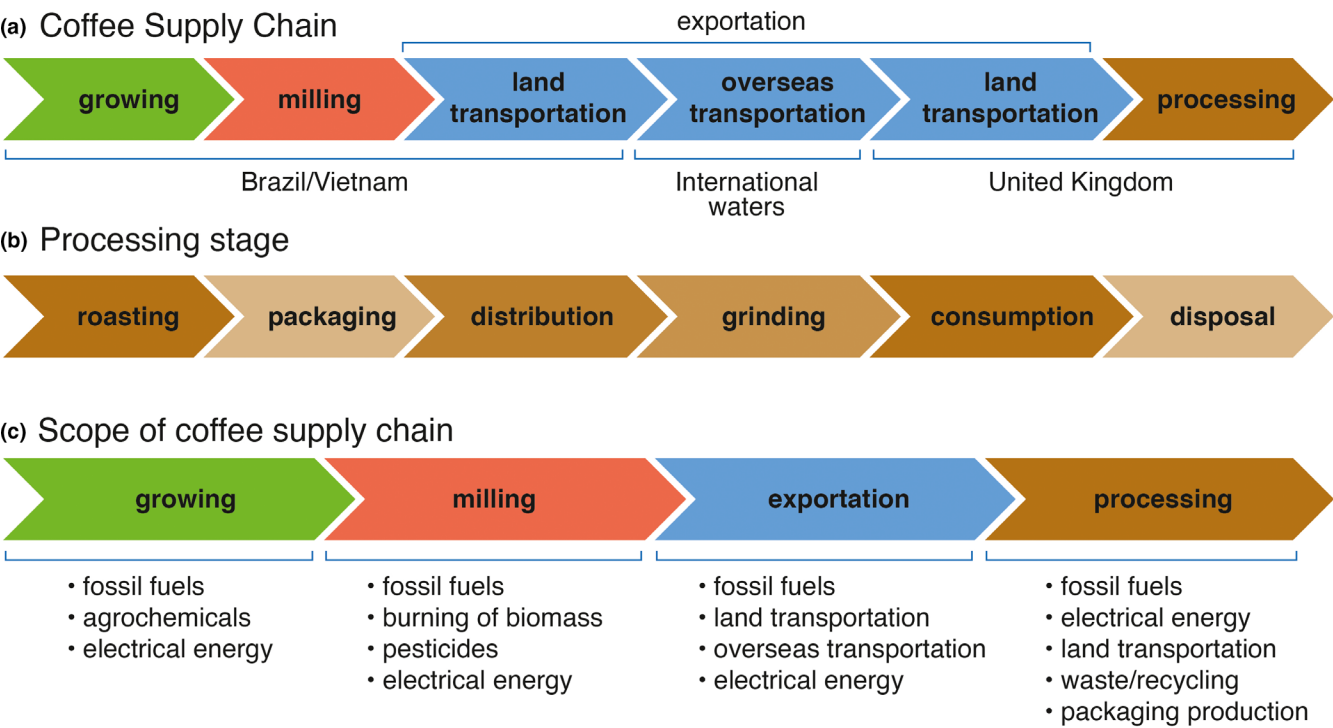 - packaging production

FIGURE 4 Different stages of coffee processing with potential sources of carbon emissions (adapted from Killian et al., 2013).

6.1 | Life cycle inventory

A life cycle inventory was created, identifying the main inputs at the first three stages of coffee production; growing, milling, and exportation. The inputs required for the growing and milling stages were taken from LCAs carried out by De Marco et al. (2018) and Arce et al. (2009), respectively (Table 1). These are generic data and therefore it was not possible to differentiate differences between growing and milling in the two case study countries. The input units used for these stages are average inputs required to produce 1 kg of green Arabica coffee beans on conventional and sustainable coffee farms in a tropical environment. The coffee farm locations were placed at random points in Sao Paulo (Brazil) and Buôn Ma Thu t (Vietnam), the biggest coffee producing regions in the countries (ICO, 2019). The nearest ports and international airports to these coffee farms were then identified using sea-distances.org (2019) and Google Maps (2019). The transport distances from these ports to the Port of Bristol were then estimated using Google Maps (van distance, freight flight distance) and sea-distances.org (cargo ship distance) for the exportation phase (Table 1).

Based on emission hotspots identified by previous LCAs, the sustainable case studies varied from the conventional ones in three ways: the use of organic waste instead of artificial fertilisers, the lack of pesticides, and the exportation of coffee beans to the United Kingdom via cargo ship rather than freight flight. Additionally, increased efficiency in the milling phase meant a reduction in water, electricity, and fossil fuel use in the sustainable case studies (Table 1).

6.2 | Carbon footprint calculation

The carbon footprint quantification methodology was based on combined guidance from PAS 2050:2011 (DEFRA and BSI, 2011) and the IPCC's National Greenhouse Gas Inventories (IPCC, 2006). The footprint of each emissions factor was determined using conversion factors provided by the UK Government and DEFRA. Country-specific conversion factors on electricity and fossil fuels used for inputs based in Brazil and Vietnam to account for variation caused by the sources of inputs (e.g., electricity). A spreadsheet model was created to calculate the carbon footprint, into which all the collected data and emission factors were entered.

6.2.1 | Step 1: calculating coffee production

To start, the amount of coffee produced or processed at every stage was determined, by which the emissions at each stage could be divided to determine the carbon footprint of a specific source of emissions for one functional unit. The information on coffee is presented as a function of 1 kg of green coffee beans.

6.2.2 | Step 2: calculating carbon emissions

To calculate the emissions of each source, its input value, presented in the life cycle inventory, was multiplied by its specific emission factor. Different conversion factors were used to calculate these conversion factors: electricity and fossil fuel emissions were calculated using the national average electricity and fossil fuel emissions factors for Brazil and Vietnam, provided by DEFRA (2012). Emissions for water, firewood, and transportation were obtained from the UK Government, (2019). Fertiliser and pesticide emission factors provided by DEFRA (2012) were used.

6.2.3 | Step 3: carbon footprint calculation

The emissions at each stage of coffee production were totalled and standardised in kg of CO_{2e}. These emissions were then divided by the total amount of coffee produced or processed at each stage, resulting in the carbon footprint of each stage expressed in kg CO_{2e} kg^{-1} green coffee.

The carbon footprint was calculated separately for each case study, resulting in four quantifications: conventional coffee from Brazil; conventional coffee from Vietnam; sustainable coffee from Brazil; and sustainable coffee from Vietnam. This was done to allow for the comparison between conventional and sustainable coffee and between separate coffee growing regions, Latin America and Southeast Asia.

After extensive evaluation of the available literature, the following data sources were chosen to complete the life cycle inventory:

TABLE 1 Life cycle inventory of the main inputs and outputs for conventional and sustainable coffee production in Brazil (top) and Vietnam (bottom); data refer to 1 kg of green coffee beans

Brazil conventional					Brazil sustainable				
Parameter	**Unit**	**Value**	**Comments**	**Value source**	**Parameter**	**Unit**	**Value**	**Comments**	**Value source**
Growing					Growing				
Fertiliser	kg	0.23		De Marco et al. (2018)	Fertiliser	kg	0.50	organic waste only	De Marco et al. (2018)
Fossil fuels	kg	0.01		De Marco et al. (2018)	Fossil fuels	kg	0.01		De Marco et al. (2018)
Electricity	kg	0.11		De Marco et al. (2018)	Electricity	kg	0.11		De Marco et al. (2018)
Pesticides	kg	0.01		De Marco et al. (2018)	Pesticides	kg	0.00	No pesticides	De Marco et al. (2018)
Milling					Milling				
Water	L	22.05		Arce et al. (2009)	Water	L	0.79		Arce et al. (2009)
Electricity	kWh	0.26		Arce et al. (2009)	Electricity	kWh	0.04		Arce et al. (2009)
Fossil fuels	kg	0.03		Arce et al. (2009)	Fossil fuels	kg	0.03		Arce et al. (2009)
Fuel (firewood)	kg	1.54		Arce et al. (2009)	Fuel (firewood)	kg	1.54		Arce et al. (2009)
Exportation					Exportation				
Van/lorry distance	km	14.00		Google Maps (2019)	Van/lorry distance	km	101.00		Google Maps (2019)
Freight flight distance	km	9,353.39		Google Maps (2019)	Freight flight distance	km	9,660.03		sea-distances.org (2019)
Van distance	km	27.00		Google Maps (2019)	Van distance	km	1.60		Google Maps (2019)
Outputs					Outputs				
Green coffee	kg	1.00	Functional unit		Green coffee	kg	1.00	Functional unit	
Vietnam conventional					**Vietnam sustainable**				
Parameter	**Unit**	**Value**	**Comments**	**Value source**	**Parameter**	**Unit**	**Value**	**Comments**	**Value source**
Growing					Growing				
Fertiliser	kg	0.23		De Marco et al. (2018)	Fertiliser	kg	0.50	organic waste only	De Marco et al. (2018)
Fossil fuels	kg	0.01		De Marco et al. (2018)	Fossil fuels	kg	0.01		De Marco et al. (2018)
Electricity	kg	0.11		De Marco et al. (2018)	Electricity	kg	0.11		De Marco et al. (2018)
Pesticides	kg	0.01		De Marco et al. (2018)	Pesticides	kg	0.00	No pesticides	De Marco et al. (2018)
Milling					Milling				
Water	L	22.05		Arce et al. (2009)	Water	L	0.79		Arce et al. (2009)
Electricity	kWh	0.26		Arce et al. (2009)	Electricity	kWh	0.04		Arce et al. (2009)

(Continues)

TABLE 1 (Continued)

Vietnam conventional					Vietnam sustainable				
Parameter	**Unit**	**Value**	**Comments**	**Value source**	**Parameter**	**Unit**	**Value**	**Comments**	**Value source**
Fossil fuels	kg	0.03		Arce et al. (2009)	Fossil fuels	kg	0.03		Arce et al. (2009)
Fuel (firewood)	kg	1.54		Arce et al. (2009)	Fuel (firewood)	kg	1.54		Arce et al. (2009)
Exportation					Exportation				
Van/lorry distance	km	338.00		Google Maps (2019)	Van/lorry distance	km	333.00		Google Maps (2019)
Freight flight distance	km	10,372.04		Google Maps (2019)	Freight flight distance	km	16,169.81		sea-distances.org (2019)
Van distance	km	27.00		Google Maps (2019)	Van distance	km	1.60		Google Maps (2019)
Outputs					Outputs				
Green coffee	kg	1.00	Functional unit		Green coffee	kg	1.00	Functional unit	

- Growing phase: De Marco (2018) – an LCA of Arabica coffee production in Brazil and Vietnam, with data put together from a mix of peer-reviewed literature, primary data from coffee producers, and interviews with coffee farmers.
- Milling phase: Arce (2009) – a study comparing the environmental footprint of conventional and sustainable coffee farming in Latin America, with data for conventional production taken from ICAFE (2017) and compared with primary data compiled from a number of sustainable coffee processors. Whilst not as recent as De Marco (2018), this was chosen as it included the evaluation of primary data from multiple coffee farms.

Though the literature is limited for coffee production, these sources were selected as they were deemed the most comprehensive and provided clear data inputs for each stage of the coffee life cycle, for both conventional and sustainable Arabica coffee. These studies were based largely on primary data collected at coffee farms and mills, which were collated with results from peer-reviewed academic literature to estimate inputs at each stage.

The use of an LCA was appropriate as it quantifies carbon emissions released by each input of the product's life cycle, thus allowing for the accurate estimation of the carbon footprint of each phase of production. Additionally, the quantification of GHG emissions as a combined CO_{2e} value was suitable as it factors in the climatic potential of each gas included and allows for a comparison of the overall climatic impact of products that emit different GHGs.

6.3 | Growing, milling, and exportation phases

The carbon footprints estimated for conventional coffee production in Brazil and Vietnam were 11.56 and 12.99 kg CO_{2e} kg^{-1} green coffee, respectively, from farm level to a storage location in Bristol (Table 2, upper panel). The proportion of the carbon footprint contributed by each stage is similar for both countries, with the majority of the emissions coming from the freight flight transport between the producing countries and the United Kingdom (10.42 and 11.55 kg CO_{2e} kg^{-1}, respectively). This flight was calculated to contribute 98–100% of emissions produced in the exportation phase and 90% of total emissions produced in the growing, milling, and exportation phases. In the growing phase, the use of fertilisers was the largest source of CO_{2e} emissions (95% and 92%), whilst in the milling phase fossil fuel use (77% and 45%) and electricity use (16% and 51%) made the highest contributions.

The carbon footprints estimated for sustainable coffee production in Brazil and Vietnam were much lower, totalling 0.32 and 0.59 kg CO_{2e} kg^{-1} green coffee, respectively, for the growing, milling, and exportation phases (Table 2, lower panel). Whilst still the largest contributor, the exportation phase was responsible for 59% and 70% of total CO_{2e} emissions for Brazil and Vietnam, respectively, with the cargo ship transport from port to port contributing 67% and 50% of emissions in the exportation phase. The use of organic waste as fertiliser and lack of pesticide use made fossil fuel use (66% and 39%) and electricity use (16% and 51%) the largest emission sources in the growing phase. In the milling phase, fossil fuel use

TABLE 2 Carbon footprint at each phase of conventional and sustainable coffee production

Conventional

Brazil				Vietnam		
Emission source	CO₂ emission kg CO_{2e} kg^{-1} green coffee	%		Emission source	CO₂ emission kg CO_{2e} kg^{-1} green coffee	%
Growing				Growing		
Fertiliser	0.96	95		Fertiliser	0.96	92
Fossil fuels	0.03	3		Fossil fuels	0.03	3
Electricity	0.01	1		Electricity	0.04	4
Pesticides	0.01	1		Pesticides	0.01	1
Total	1.01	100		Total	1.04	100
Milling				Milling		
Water	0.01	7		Water	0.01	4
Electricity	0.02	16		Electricity	0.09	51
Fossil fuels	0.08	77		Fossil Fuels	0.08	45
Fuel (firewood)	0.00	0		Fuel (Firewood)	0.00	0
Total	0.10	100		Total	0.18	100
Exportation				Exportation		
Farm to airport	0.01	0		Farm to airport	0.21	2
Airport to airport	10.42	100		Airport to airport	11.55	98
Airport to storage	0.02	0		Airport to storage	0.02	0
Total	10.44	100		Total	11.77	100

Sustainable

Brazil				Vietnam		
Emission source	CO₂ emission kg CO_{2e} kg^{-1} green coffee	%		Emission source	CO₂ emission kg CO_{2e} kg^{-1} green coffee	%
Growing				Growing		
Fertiliser	0.01	17		Fertiliser	0.01	10
Fossil fuels	0.03	66		Fossil fuels	0.03	39
Electricity	0.01	16		Electricity	0.04	51
Pesticides	0.00	0		Pesticides	0.01	0
Total	0.05	100		Total	0.08	100
Milling				Milling		
Water	0.00	0		Water	0.00	0
Electricity	0.00	3		Electricity	0.02	16
Fossil fuels	0.08	96		Fossil fuels	0.08	84
Fuel (firewood)	0.00	0		Fuel (firewood)	0.00	0
Total	0.08	100		Total	0.10	100
Exportation				Exportation		
Farm to airport	0.06	33		Farm to airport	0.20	50
Airport to airport	0.12	67		Airport to airport	0.21	50
Airport to storage	0.00	1		Airport to storage	0.00	0
Total	0.19	100		Total	0.41	100

remained the largest emission source, contributing 96% and 84% of emissions in Brazil and Vietnam, respectively. In total, the carbon footprint of conventional coffee production was 36 and 22 times higher than sustainable production in Brazil and Vietnam, respectively.

6.4 | Processing phase

An LCA on coffee processing by PCF Pilotprojekt Deutschland (2008) calculated a carbon footprint of 3.05 kg CO_{2e} kg^{-1} green coffee, with 70% of emissions associated with consumption, followed by grinding (10%), roasting (6%), distribution and disposal (5%), and packaging (4%).

6.5 | Total carbon footprint

By combining all the stages including the processing phase (Figure 5), conventional coffee from Vietnam was calculated to have the highest carbon footprint (16.04 kg CO_{2e} kg^{-1} green coffee) followed by conventional coffee from Brazil (14.61 kg CO_{2e} kg^{-1} green coffee), though the primary difference between these two was the transportation distance. Sustainable coffee from Vietnam (3.64 kg CO_{2e} kg^{-1} green) and sustainable coffee from Brazil (3.37 kg CO_{2e} kg^{-1} green) were much lower, and again the differences were due to different transport distances. For conventional coffee production, the exportation process was calculated to produce over 70% of total CO_{2e} emissions in both case studies. The processing phase was the second largest source of emissions (19%–21%) followed by the growing (7%) and milling (1%) phases. In the case of sustainable coffee, the processing phase was by far the largest source of CO_{2e} emissions, contributing 91% for Brazil and 84% in Vietnam. Exportation was responsible for 6–11% of total CO_{2e} emissions, followed by milling (2–3%) and growing (1–2%). PAS 2050 classifies emissions exceeding 5 kg CO_{2e} kg^{-1} as "very high intensity," whilst those between 0.1 and 1.0 kg CO_{2e} kg^{-1} are classed as "medium intensity" (DEFRA and BSI, 2011). At over 10 kg CO_{2e} kg^{-1}, both case studies of conventional coffee production assessed would be classed as very high intensity, whilst those for sustainable coffee production are considered to be of medium intensity.

With a drink containing approximately 18 g of green coffee (Starbucks Coffee Company, 2019), each kg of green coffee makes approximately 56 espresso beverages. Thus, the carbon footprint found in the LCA is on average 0.28 and 0.06 kg CO_{2e} per espresso beverage for conventional and sustainable coffee, respectively (9.2 and 2.1 g CO_{2e} ml^{-1}). In an LCA of
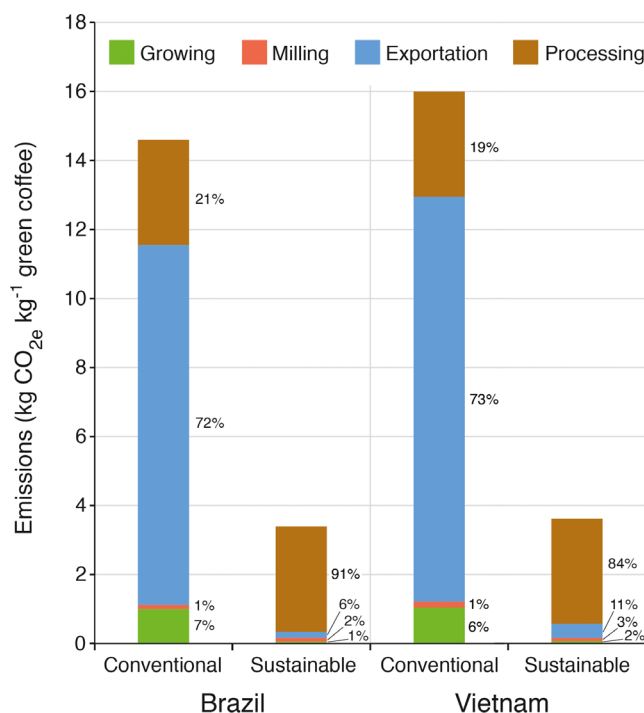

FIGURE 5 The contribution of each phase to the total carbon footprint of coffee production (percentages may not add up due to rounding).

milk production, Hassard et al. (2014) estimated a carbon footprint of 2.26 g CO_{2e} ml^{-1}. Using these values, the carbon footprint of standard coffee beverages was estimated: with the conventional production of coffee beans, the carbon footprints for one serving of caffe latte, flat white, and cappuccino were estimated to be 0.55, 0.34, and 0.41 kg CO_{2e}, respectively. When produced sustainably, these values were reduced to 0.33, 0.13, and 0.20 kg CO_{2e}. Whilst the carbon footprint of coffee production is four times higher than that of milk (per ml) for conventional production and equal to that of milk for sustainable production, the larger proportion of milk than coffee used in these beverages resulted in a significant increase in carbon footprint. For conventional coffee production, the carbon footprint increased by 25% (flat white), 50% (cappuccino), and 100% (caffe latte) in comparison to espresso (Figure 6). When produced sustainably, the large decrease in the carbon footprint of coffee meant that the difference was even larger, increasing by 205% (flat white), 315% (cappuccino), and 530% (caffe latte) in comparison to espresso (Figure 6).

These estimations were higher than those made by Hassard et al. (2014), who calculated carbon footprints of 0.049 kg (espresso) and 0.224 g CO_{2e} (caffe latte) per serving. This is largely due to their use of Japan as the country of both production and consumption, omitting the exportation phase quantified in this study. Additionally, Hassard et al.'s LCA of milk only included direct emissions created in the production phase, omitting indirect emissions such as methane produced by cows. An LCA by de Boer (2003) estimated that the emission of methane from cows adds an additional 48–65% to the global warming potential of milk production, increasing its carbon footprint to 3.35–3.73 g CO_{2e} ml^{-1}.

7 | DISCUSSION

7.1 | Major contribution to coffee total carbon footprint

When interpreting the LCA results, it is important to consider that the lack of real farm data regarding emissions means that the environmental impact calculated with an LCA may differ from the actual environmental impact (Thomassen et al., 2008). The LCA also does not provide any insight into the other environmental impacts of coffee production, including deforestation, biodiversity loss, water pollution, and eutrophication (reference).

These case studies presented here demonstrate the importance of the exportation phase, with significant emissions with conventional coffee if international freight flights are used. Sustainable coffee production with no air transport, a large part of the emissions are in the processing phase. Previous LCAs placed the largest proportion of CO_{2e} emissions in the processing and production phases, with the exportation phase attributed to less than 5% of total CO_{2e} emissions. Whilst the coffee farms investigated in these studies were largely similar to those studied in the conventional case studies, they
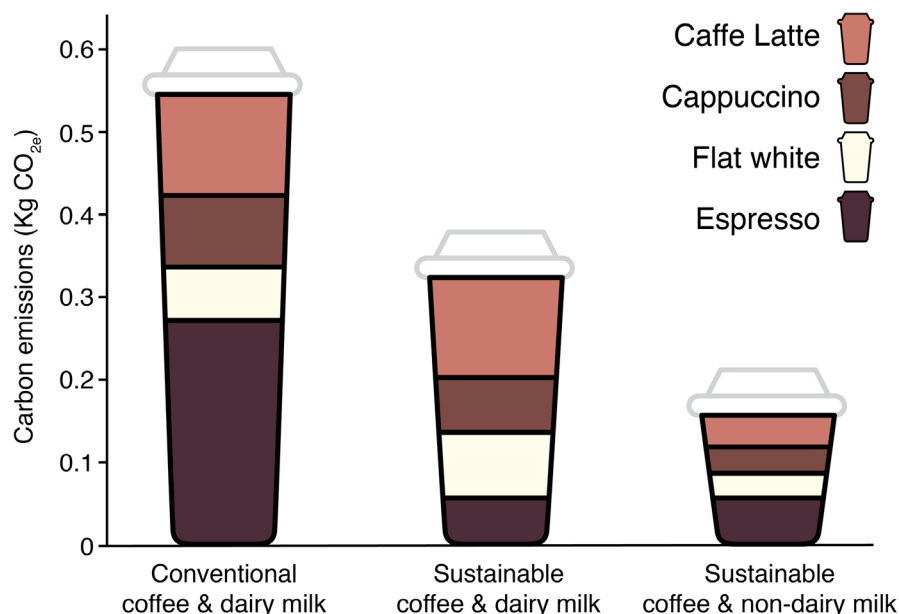

FIGURE 6 Comparison of the carbon footprint of different styles of coffee using conventional or sustainable coffee and diary milk or non-diary milk. Weight of coffee per cup was from Starbucks Coffee Company (2019); coffee carbon footprint from this study and milk carbon footprint from Poore and Nemecek (2018).

included the international transport of coffee beans via cargo ship, explaining the small proportion of emissions attributed to the exportation phase.

The sustainable case studies quantified in this study had an estimated 77% lower carbon footprint than the conventional case studies, mainly as a result of two sustainability measures. First, the use of cargo ships for the transportation of coffee beans from the production countries to the United Kingdom instead of freight flights reduced estimated emissions by 10.3–11.3 kg CO_{2e} kg^{-1} green coffee. Although transportation via cargo ship takes significantly longer, with transport time increasing from 12 hours to two weeks (24 times longer) for Brazil and 14 hours to three weeks (48 times longer) for Vietnam (sea-distances.org, 2019), this method of transportation can export significantly larger shipments of coffee beans at once. Second, the replacement of chemical fertilisers with organic waste in the sustainable case studies reduced estimated emissions by 0.95 kg CO_{2e} kg^{-1} green coffee. An LCA of coffee production in Vietnam, based on interview data, found that most coffee farmers apply excess chemical fertilisers (on average 0.6 kg plant^{-1} year^{-1}) with the belief that this will increase coffee yield linearly. In fact, a report from the Chumphon Horticultural Research Center (2011) calculated an optimal fertiliser application rate of 0.24 kg plant^{-1} year^{-1}. Their study found that any excess fertiliser could not be absorbed by the coffee plants, instead leaching into nearby surface water, resulting in nitrous oxide emission and water pollution. Based on this report, Ratchawat et al. (2018) estimated that the carbon footprint of coffee could be reduced by 12% if farmers followed this recommendation, saving them around £17/ha on the cost of chemical fertilisers.

The lack of pesticide use in the production phase and reduced use of water and electricity in the milling phase further reduced the estimated carbon footprint of the sustainable case studies in comparison to the conventional ones, albeit at a significantly smaller scale (<0.1 kg CO_{2e} kg^{-1} green coffee reduction each).

7.2 | Further potential reductions of the carbon footprint of coffee production

7.2.1 | Use of recycled materials and reduction of packaging amount

This reduces the demand for primary materials, thus reducing energy, water, and material consumption, air and water emissions in the production of packaging materials, and impacts on biodiversity from forestry and mining (von Geibler et al., 2016). An LCA by the Alliance for Environmental Innovation (2000) estimated carbon footprints of 0.52, 0.22, and 0.18 kg CO_{2e} per serving for paper, polystyrene, and ceramic cups, whilst Arena et al. (2003) estimated a carbon footprint reduction of up to 85% where recycled plastic was used to produce packaging in comparison to virgin plastic.

7.2.2 | Increasing efficiency in water heating

In the processing phase, an estimated 70% of CO_2 emissions were attributed to consumption, largely due to the significant energy use of automatic coffee machines (see PCF Pilotprojekt Deutschland, 2008). This energy use could be reduced by using more efficient water using technologies – although this is largely in the hands of the consumer – and the design of more efficient coffee machines. The addition of milk and/or sugar was not considered in this study.

7.2.3 | Use of renewable energy sources

The use of fossil fuels for electricity and energy production releases significant air emissions during each phase of the coffee life cycle (von Geibler et al., 2016). An LCA by IRENA (2017) estimated that the use of renewable energy sources can reduce the carbon footprint of crop production by up to 70%. Based on the carbon footprints calculated in this study, the use of renewable energy sources instead of fossil fossils could reduce the carbon footprint of coffee production by 0.11 kg CO_{2e} kg^{-1} green coffee (not including the processing phase).

7.2.4 | Roasting the coffee beans in the producing country

Currently, coffee is usually exported to the country of consumption before it is roasted, allowing retailers to market their coffee as "freshly roasted." Whilst green coffee beans have a longer shelf life than roasted ones, roasted coffee beans can retain their fresh taste up to six months if stored at cool temperature (below 10°C) in air-tight laminated aluminium layer, one-way valve and nitrogen flushed packaging (Josephy, Bush, Nipkow, & Pilone, 2013; Smrke, 2020). Roasting coffee beans reduces their weight by more than half but the volume remains approximately the same. This makes a big difference to air freight which is focused mainly on weight but less important for international shipping that is mainly concerned with

volume. Roasting the coffee beans before exporting them could reduce the carbon footprint in the exportation phase dependent on the method of exportation. This would also allow producer countries to move up the value chain and have associated development advantages; this more than offset the downside of roasted and ground coffee being more perishable.

In addition to making these sustainable changes to the coffee life cycle, coffee retailers could offset their entire carbon footprint at a miniscule price of around £0.15 and £0.03 per kg of green coffee produced for conventional and sustainable coffee production, respectively (£0.01 per kg CO_{2e}; Conservation International, 2019a), based on the carbon footprints calculated in this study. Carbon offsetting does, however, require due diligence to ensure "good quality" offsets that will produce the desired environmental benefits and should be seen as an additional environmental measure rather than a primary solution.

7.2.5 | Land use change

Although the amount and location of land used for coffee production has remained relatively stable over the past 20 years (Babin, 2014), one of the most frequently hypothesised but understudied results of the increasing demand for coffee is the switch from coffee agroecosystems to monoculture systems with little ecological benefits. The carbon sequestration potential of agroforestry systems is well documented, particularly for products such as coffee and cocoa, for which gross carbon sequestration has been estimated to outweigh GHG emissions throughout their lifetime (Fitriani, Zakaria, & Ismono, 2018). Whilst the intensification of existing agriculture allows for the avoidance of carbon emissions from land use change, intensive monoculture coffee plantations do not have this carbon sequestration potential. A carbon performance study in Costa Rica and Nicaragua found that, whilst the highest yield and greatest profits were found in "full-sun" coffee systems completely lacking shade trees, these systems had the least potential for carbon sequestration (Noponen, 2012). To incentivise the continued maintenance of existing coffee agroecosystems and compensate for the coffee production revenue lost, sustainability certification schemes such as Fair Trade have introduced a premium pricing scheme, which guarantees a higher retail price for coffee grown under Fair Trade standards (Babin, 2014). Noponen (2012) also found that, if maintenance of less productive coffee agroecosystems results in the expansion of coffee production into areas of currently forested land to compensate for the reduced yield, this land use change will release a mammoth 5,000 kg CO_{2e} ha^{-1} year^{-1} of GHG emissions. Thus, mechanisms that are based on reducing emissions by avoiding land-use change whilst intensifying productivity of agricultural systems, such as the UN-REDD programme, could play a major role in reducing pressure for forest conversion to agriculture and increasing agroforestry systems' climate change mitigation success. Moreover, with the increased risk from raised temperature due to climate change (Bunn et al., 2015) more and more coffee production regions will have to have shade species to protect the coffee plants (Wintgens, 2008), which will increase carbon sequestration and increase local biodiversity.

7.2.6 | The processing phase

In the sustainable coffee production case studies, more than 80% of the CO_{2e} emissions were produced in the processing phase. Of the 3.05 kg CO_{2e} kg^{-1} green coffee estimated, 70% was attributed to the consumption of coffee. The source study found that a main emission driver is the preparation of coffee using an automatic coffee machine, which generates an estimated 60.27 g CO_{2e} per cup of coffee, in comparison to an estimated 10.04 g by traditional filter drip and French press methods, largely due to a six-fold increase in electricity use (PCF Pilotprojekt Deutschland, 2008). Consumers therefore play a critical role in reducing the carbon footprint of coffee production and should be encouraged to reduce their energy usage through consumer-focused awareness campaigns. To support this, manufacturers have made significant strides to increase the energy efficiency of coffee machines in recent years. Measures such as auto-power-down, low or zero standby consumption, and better insulation of hot parts have been introduced to enhance energy efficiency. As of 2013, automated coffee machines had a market share of 23% in the EU, with an annual growth of 5.5% (Josephy et al., 2013). The extremely strong trend towards espresso portioned machines means that increasing energy efficiency is crucial to decreasing the carbon footprint of coffee consumption. From 2013, coffee machines sold in the EU must have a power management function that automatically switches the machines to a standby or off mode after the shortest possible time period of intended use (Josephy et al., 2013). The introduction of an energy label would be very effective in helping buyers recognise the most efficient machines on the market. As retailers strive towards offering products of best label classes, an energy label would incentivise the coffee industry to develop more energy efficient coffee machines. When producing this label, the energy and resource consumption associated with the production of coffee capsules and pads should be taken into account.

7.3 | Comparison of coffee to other agricultural products

Average carbon footprints of conventional and sustainable coffee production in this study are 15.33 ($\pm$0.72) and 3.51 ($\pm$0.13) kg CO_{2e} kg^{-1} green coffee. In comparison to other highly traded agricultural products, the carbon footprint of coffee is relatively high, with animal products and highly processed products often having the highest carbon footprints: Beef = 27 kg CO_{2e} kg^{-1} (Wiedemann et al., 2015); cheese = 13.5 kg CO_{2e} kg^{-1} (Canellada et al., 2018); tea = 7.1 kg CO_{2e} kg^{-1} (Cichorowski et al., 2015); bananas = 1.28 kg CO_{2e} kg^{-1} (Roibás et al., 2016); wine = 1.72 kg CO_{2e} L^{-1} (Pattara et al., 2012); sugar = 0.55 kg CO_{2e} kg^{-1} (Yuttitham et al., 2011). The high quantity of coffee produced yearly means that the coffee sector has a significant total carbon footprint. Based on the results, coffee production can be attributed to a total of 33.3–125.6 billion kg of global annual CO_{2e} emissions. This is comparable to the total annual CO_2 emissions of Denmark (33.9 billion kg) and the Philippines (137.2 billion kg), as calculated by the European Commission (2017). In comparison, global tea production can be attributed to roughly 36.9 billion kg (Cichorowski et al., 2015), when exported via cargo ship, similarly to sustainable coffee production. The lack of nutritional value of both coffee and tea means that they can be considered luxury products, sometimes called "drug foods," as they are unnecessary for human survival, making their large carbon footprints arguably much worse than those of products with high nutritional values.

8 | CONCLUSIONS

Our coffee carbon footprint analysis shows there is a significant difference between sustainable and conventional coffee. This is largely due to the exportation of coffee beans via cargo ship rather than freight flight and the reduction of agrochemical inputs. This footprint could be further reduced by more efficient use of packaging materials, increased efficiency in water heating, use of renewable energy sources, roasting beans before exportation, and carbon offsetting. With growing competition and global coffee demand, retailers are increasingly transporting coffee beans via freight flight to get fresher coffee. This makes it unlikely that they will switch back to cargo ship transport, despite the large climate change mitigation potential, exposing the need for a tax on aviation fuel and/or a tax on flying luxury goods such as coffee and tea.

Despite the widespread agreement that sustainable production practices are better for the environment, our sustainable case study carbon footprint was only 24% lower than that of the conventional case studies (excluding the exportation phase). There are also concerns that by focusing on the carbon footprint of production, other environmental impacts are being missed. Hence, sustainability certification schemes must be holistic in their approach and avoid the obsession with just carbon emissions. Carefully thought out and financed certification schemes could reduce the environmental impact of coffee by educating farmers on optimal fertiliser and pesticide inputs, soil fertility conservation and water conservation, whilst maintaining high yields and reducing production costs, increasing the profitability of coffee while reducing carbon emissions (ITC, 2011).

Coffee cultivation faces an uncertain future, with climate change predictions suggesting a 50% reduction in the suitable growing area by 2050 (Bunn et al., 2015) at the same time as a tripling of demand. One adaptation is to ensure there are shade species to reduce the maximum temperature and damage to the coffee plants (Wintgens, 2008). Some certification schemes do include climate change adaptation measures, such as paying a premium for agroforestry system cultivated coffee as opposed to intensive monoculture coffee plantations (Noponen, 2012). This needs to be expanded to all certification schemes and imbedded in international agreements such as REDD + and the Bonn Accord to protect the environment and the livelihoods of coffee producers.

DATA AVAILABILITY STATEMENT

All data used in this paper are referenced in the reference list.

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