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Title: Carbon and water footprint of coffee consumed in Finland—life cycle assessment

Year: 2020

Version: Published version

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Please cite the original version:

Usva, K., Sinkko, T., Silvenius, F. et al. Carbon and water footprint of coffee consumed in Finland—life cycle assessment. *Int J Life Cycle Assess* (2020). <https://doi.org/10.1007/s11367-020-01799-5>.

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**The International Journal of Life
Cycle Assessment**

ISSN 0948-3349

Int J Life Cycle Assess
DOI 10.1007/s11367-020-01799-5



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Carbon and water footprint of coffee consumed in Finland—life cycle assessment

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Received: 4 March 2020 / Accepted: 28 July 2020
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Abstract

Purpose Coffee is one of the most widely grown cash crops globally, but there are few scientific articles on its carbon footprint and water scarcity impacts. The aim of this study was to assess the carbon footprint and water scarcity impacts throughout the life cycle of the coffee chain (cradle-to-grave) and to identify the most important sources of the impacts (hotspots).

Methods The system included all the key stages of the supply chain from land use change and coffee cultivation to roasting and household consumption. Primary data was collected from eight coffee cultivation farms in Brazil, Nicaragua, Colombia and Honduras and coffee roastery and packaging manufacturers in Finland. The AWARE method was applied in a water scarcity impact assessment.

Results and discussion The carbon footprint varied from 0.27 to 0.70 kg CO₂ eq/l coffee. The share of the coffee cultivation stage varied from 32 to 78% and the consumption stage from 19 to 49%. The use of fertilizers was the most important process contributing to the carbon footprint. Furthermore, deforestation-related emissions notably increased the carbon footprint of coffee from Nicaragua. Compared with the previous literature, our results indicate a relatively larger share of climate impacts in the cultivation stage and less during consumption.

The water scarcity impact was relatively low for non-irrigated systems in Central America, 0.02 m³ eq/l coffee. On Brazilian farms, irrigation is a major contributor to the water scarcity impact, varying from 0.15 to 0.27 m³ eq/l coffee.

Conclusions Improving the management practices in cultivation and fertilization is key for lower GHG emissions. Irrigation optimization is the most important mitigation strategy to reduce water scarcity impact. However, actions to reduce these two impacts should be executed side by side to avoid shifting burdens between the two.

Keywords Life cycle assessment · LCA · Coffee · Water scarcity · Water footprint · Carbon footprint

1 Introduction

Coffee is one of the most widely grown and traded cash crops in the world with over 10 million ha of land devoted to its

production (FAO 2018). In 2017 green coffee production in the world was around 159 million bags (60 kg) (USDA 2017). The volume of coffee consumed has shown strong growth over the last 50 years (2% annual growth rate) (ICO 2014). Now, over 70 countries produce coffee, but over 50% comes from just three countries: Brazil, Vietnam and Indonesia, and coffee exports are a key source of national income for many developing countries (FAO 2015).

Per capita, Finland is the world's second-leading coffee drink consuming country with an average consumption of 184.9 l of coffee per year per capita (after the Netherlands at 260.4 l per year per capita) (Statista 2015) and is the leading green coffee consumer (Worldatlas 2018). According to (Poore and Nemecek (2018, Supplementary material Data S2), the coffee supply chain contributes about 1% of the climate impact and 0.02% of the water scarcity impact of the total global diet.

Responsible editor: Greg Thoma

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11367-020-01799-5>) contains supplementary material, which is available to authorized users.

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Arabica coffee cherries are cultivated at high altitudes either in the subtropical regions with well-defined rainy and dry seasons, e.g. in the Minas Gerais region of Brazil or in Mexico, resulting in one coffee growing season per year or in the equatorial regions with frequent rainfall, e.g. in Kenya, Ethiopia and Colombia. Robusta coffee is grown at much lower altitudes. Green coffee is produced by processing coffee cherries at the site or in the close vicinity. Green coffee is transported to the country of consumption, roasted, packed and delivered to the consumer, who prepares and consumes the coffee drink.

The consumption and cultivation (primary production) stages are the most important contributors to the carbon footprint in the coffee chain (e.g. Büsser and Jungbluth 2009; Hicks 2017; Humbert et al. 2009; Killian et al. 2013; Salomone 2003). According to Humbert et al. (2009), about half of the climate impacts of the coffee chain are under the control of the coffee producer or its suppliers including the primary production and processing stages, and the other half is controlled by the consumer. Furthermore, Killian et al. (2013) conclude that 45% of the carbon footprint originates from the use stage and 21% from the primary production and the results by Salomone (2003) support this.

During cultivation, the main contributor to GHG emissions stems from the application of N-fertilizer in the farming stage (Hergoualch et al. 2008; Noponen et al. 2012; Segura and Andrade 2012; Andrare et al. 2014; Killian et al. 2013). According to Killian et al. (2013), 94% of the emissions come from fertilizers at the farm level in coffee production. Andrare et al. (2014) report that N-fertilizers contribute 70% of the total GHG emissions from monoculture coffee plantations, and Noponen et al. (2012) specify the N₂O emission due to N-fertilizer use as the most important source of greenhouse gases in the coffee supply chain. During the use stage, different preparation methods of coffee, the use of milk, waste in general and the wastage of coffee, washing of coffee cups and electricity production have an effect on the carbon footprint. The brewing of coffee is an important factor in the use stage regarding the environmental impacts (Büsser and Jungbluth 2009; Humbert et al. 2009; Killian et al. 2013), and in the case of white coffee, milk production also increases the carbon footprint of the coffee drink (Büsser and Jungbluth 2009).

In terms of water consumption in the coffee supply chain, cultivation accounts for the most use of water if irrigation is used. In addition, coffee brewing has been reported to be the main contributor to water consumption if no irrigation is applied (Humbert et al. 2009).

Land use changes from forest to arable and perennial crops occur in many coffee-producing countries due to deforestation, for example, in parts of Central America and Brazil. Land use change causes severe climate impacts because the above-ground biomass is lost and carbon released from the soil as a consequence of deforestation, the albedo of the area

may be modified, the evapotranspiration may be changed causing changes in precipitation and reflection of solar radiation by clouds, and also the flow of greenhouse gases other than CO₂ may be modified (Müller-Wenk and Brandão 2010). Land use change is not always directly related to the cultivation of certain products, but it is a more complicated phenomenon. However, according to the PEF Guidelines (European Commission 2013), the impacts due to land use change should be assessed and reported in LCA studies so that this substantial source of GHG emissions is not neglected.

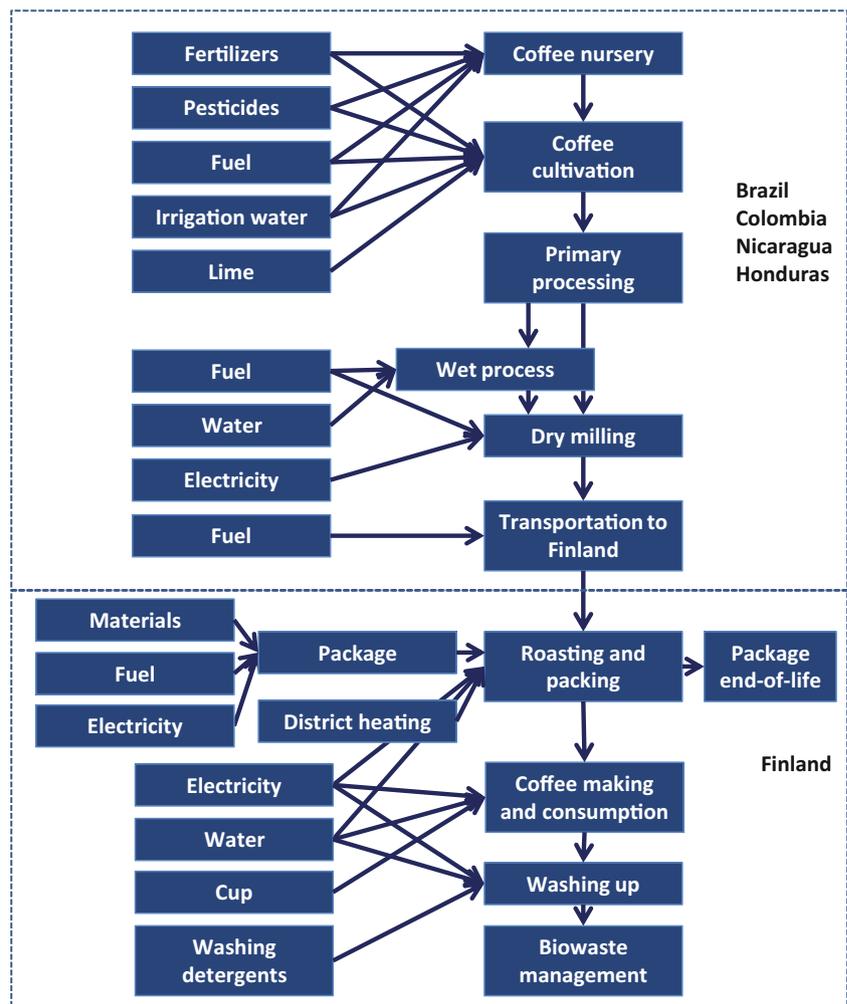
LCA studies on coffee have included the assessment of the carbon footprint (Büsser and Jungbluth 2009; Hassard et al. 2014; Hergoualch et al. 2008; Hicks 2017; Humbert et al. 2009; Killian et al. 2013; Noponen et al. 2012; Salomone 2003; Verchot et al. 2006), but only Humbert et al. (2009) have assessed water scarcity impacts, and impacts due to changes in land use have not been included at all in the scientific literature. Coffee cultivation inventories were executed in a study by Coltro et al. (2006), including 56 coffee-producing properties in four regions in Brazil, and in a study by Noponen et al. (2012) at two field sites in Costa Rica and Nicaragua. However, coffee producers need reliable information on the environmental impacts of this crop from the primary production all the way to consumers to be able to improve their environmental performance, develop responsible practices and to obtain a solid base for communicating the sustainability of their product.

We used life cycle assessment methods defined in ISO standards (ISO 2006a, b, 2014) to estimate the carbon footprint and water scarcity impact (LCA) of Arabica coffee produced in Finland by Paulig Ltd., also taking the greenhouse gas emissions related to land use change into account. The specific goals were to determine the most important stages of this specific coffee production chain and to find targets for possible further development work. In the paper, we present the hotspots of the coffee roasted and consumed in Finland in terms of carbon footprint and water scarcity impact categories, and we discuss the impacts of cultivation as well as consumption stages. The green coffee inventories were located in Brazil, Nicaragua, Colombia and Honduras, and the data was collected altogether from eight farms.

2 Materials and methods

2.1 System boundaries, functional unit and impact assessment methods

The system studied included the coffee supply chain from coffee cultivation to the use stage (Fig. 1). Inputs included into the coffee cultivation system were fertilizers, pesticides, fuels, lime, irrigation water and coffee plants. Fuel, electricity and water for primary processing (dry milling and wet

Fig. 1 System boundaries of the coffee life cycle

processes) were included as well, but waste and side flow management (i.e. wastewater treatment or composting of processing side flows) were not. The transportation of all cultivation inputs, as well as coffee cherry transportation to primary processing and green coffee transportation to Vuosaari harbour in Finland, was included. The transportation from the harbour to the roasting facility in Finland was less than 1 km and was excluded. District heating and electricity used in the roasting was included. For the package production, the package material production for items such as granulates was included, as well as conversion processes including energy use, water use and material efficiency. The end-of-life was included by using a scenario approach which involved an incineration process with energy recovery. Electricity, water, cups, filters for coffee making and washing detergent production were all within the system boundaries in the coffee making and washing stage, as well as emissions from municipal biowaste treatment related to coffee brewing waste. Infrastructure, i.e. coffee machine production, was excluded in all stages.

The functional unit of the study is 1 l of consumed coffee. In addition, some results are presented per kg of green coffee and per cup (140 ml) of coffee.

Characterization factors for greenhouse gases were used according to IPCC 2019 (Myhre et al. 2013, Table 8.7) with climate carbon feedback: 1 for carbon dioxide, 34 for biogenic methane, 36.75 for fossil methane and 298 for nitrous oxide emissions.

The water scarcity impact was calculated according to the AWARE method by Boulay et al. (2018). The indicator quantifies the potential of water deprivation to either humans or ecosystems and it is based on the available water remaining per unit of surface in a given watershed relative to the world average, after human and aquatic ecosystem demands have been met. Values range from 0.1 to 100. The country-specific characterization factors used are presented in Table 1.

Both characterization methods are used also in European Commission Product Environmental Footprint methodology (Fazio et al. 2018).

Table 1 Characterization factors for water scarcity impacts in Finland, as well as the coffee-producing countries of this study and the world average according to the AWARE method (Boulay et al. 2018)

	Finland	Brazil	Nicaragua	Colombia	Honduras	World
Agriculture	1.72	2.45	1.72	0.55	1	45.74
Non-agriculture	1.96	1.88	2.67	0.77	1.19	20.30

2.2 Data sources

For most relevant processes, primary data was obtained from the suppliers of Paulig Ltd. and its own operations. The consumer stage is based on literature data, as well as processes with only minor impacts. The data sources are explained in more detail below.

2.2.1 Data from primary production

Questionnaires were sent to the farms supplying to Paulig Ltd. to acquire inventory data on coffee cultivation and complementary data was asked when needed. Coffee cultivation data was obtained from two farms in Brazil in the Cerrado (494 ha) and Minas Gerais (30 ha), four farms in Nicaragua in San Jose de la Quilali (12 ha and 7 ha), Ocotal Nueva Segovia (4 ha) and Las Camelias San Fernando (20 ha), one farm in Colombia, in Risaralda (5 ha) and one farm in Honduras (141 ha). Nursery, cultivation and primary processing as well transportation data were asked from 3 years 2014–2016. Some exceptions were accepted due to a lack of data in answers (see Table S1).

Data was requested concerning the amounts of coffee cherries and green coffee and this was checked against the theoretical yields in the primary processing of coffee. In the case of wet processes, the theoretical yield is about 17% from coffee cherry to green coffee, even though the processing technologies vary (Sualeh and Dawid 2014). Yields from 12 to 24% were accepted. If the calculated yields were out of that range, it was assumed that the amount of green coffee was correct and the amount of coffee cherries was corrected according to the theoretical yield.

Electricity consumption varied from 0 to 240 kWh/t green coffee and diesel consumption from 3 to 61 l/t green coffee. The most relevant primary data is presented in Table 2.

Emission factors for agricultural inputs (production of fertilizers, lime and plant protection chemicals, as well as emissions from electricity use in the production countries) were based on the EcoInvent 3 (Frischknecht et al. 2005) or Agri-footprint database 4.0 (Blonk Agri-footprint 2014), from which the most similar processes to those studied were chosen. The amount of N is the most important factor in terms of the carbon footprint of a fertilizer. In cases in which NPK-fertilizers with certain N-contents were missing from the

existing datasets, the datasets were combined and estimates for relevant fertilizers were formulated. In cases where machinery was used in seedling production or cultivation, the climate impact emission factors for diesel production were based on data from NesteOil (personal communications). Water consumption for diesel production was based on the EcoInvent 3 dataset (Frischknecht et al. 2005). Some general assumptions were made to complement the data (Table 3). The density of the coffee plants and the renewal time period for coffee plants were used to assess the average consumption of new coffee plants. One out of two farms which used irrigation did not include water pumping energy to their energy consumption data, so the diesel consumption for the irrigation was assessed according to the literature data.

Direct and in-direct N₂O emissions from coffee cultivation were calculated according to the IPCC (2006) method and emission factors. The emission factor for liming is 0.12 kg CO₂-C/kg limestone applied to the soil (IPCC 2006, chapter 11).

2.2.2 Special characteristics of the case farms

Especially in Brazil, lime is applied annually due to exceptionally acidic soil conditions in the coffee production areas. High levels of liming cause extra carbon dioxide emissions compared with the other production areas in Central America.

Of the farms in this study, irrigation was used only on Brazilian farms. However, the irrigation rates differed greatly: one case farm in Minas Gerais irrigated 73 m³/t of fresh coffee berries, while another case farm in Cerrado irrigated 202 m³. Theoretical irrigation rates for agricultural products have been estimated, e.g., by Pfister and Bayer (2014) and their estimation for Brazilian coffee was higher at 1104 m³/t fresh coffee berries. In Brazil, irrigation is not used in traditional coffee production, but there was an increase in the use of irrigation two decades ago which enabled the cultivation of coffee in new areas and increased efficiency of production (Turco et al. 2017). This might explain the variation in irrigation rates.

The case farms studied in Nicaragua and Honduras cultivate and harvest coffee cherries with minimal use of machinery and their diesel consumption was assumed to be zero.

The amount of nitrogen fertilizer application varied significantly (see Fig. 2). In general, the two Brazilian farms had higher yields than the farms in Central America. Especially

Table 2 Most relevant primary data on green coffee production in case farms and primary processing

	Average	Min	Max	Unit
Farms in Brazil ¹				
Yield, coffee cherries	11,122	10,236	12,007	kg/ha
Yield, green coffee	1606	1245	1967	kg/ha
Fertilizer N	382	279	484	kg/ha
Lime	1178	1000	1360	kg/ha
Irrigation/ha	1587	750	2425	m ³ /ha
Irrigation/green coffee	917	600	1230	m ³ /t
Green beans/fresh cherry	14	12	16	%
Farms in Colombia and Honduras ²				
Yield, coffee cherries	5473	4512	6434	kg/ha
Yield, green coffee	874	718	1029	kg/ha
Fertilizer N	191	186	196	kg/ha
Green beans/fresh cherry	16	16	16	%
Water consumption in wet process/green coffee	1.9	1.8	2.0	m ³ /t
Farms in Nicaragua ²				
Yield, coffee cherries	4740	3473	5957	kg/ha
Yield, green coffee	1005	817	1386	kg/ha
Fertilizer N	116	88	154	kg/ha
Green beans/fresh cherry	21	18	24	%
Water consumption in wet process/green coffee	4.5	3.3	6.2	m ³ /t

¹ No wet processing in Brazilian farms

² No liming or irrigation in Colombian, Honduran or Nicaraguan farms

the Brazil/Cerrado and Nicaragua/San Jose de la Quilali, 2 farms had noticeably high yields compared with the nitrogen fertilizing levels, while on the other hand, the Brazil/Minas Gerais and Colombia farms had very low yields compared with N-fertilizing levels. This variation may be due to aspects such as the different ages of the coffee plants, natural variation between years (even though the data was mostly acquired for 3 years) and also some inaccuracy in the data.

Primary processing technologies also varied between the production sites. In the process, the pulp is removed from the coffee bean. Wet processing before dry milling was applied on farms in Colombia, Honduras and Nicaragua. The two Brazilian production sites used only dry milling technology. The processing stage also includes transportation from cultivation to wet or dry processing, if they are not at the same location.

The use of energy during primary processing was also subject to some variation due to the used technology. A drying

yard is a common method using only direct solar energy for drying. However, diesel fuel was used on the Brazil/Cerrado and all four Nicaraguan farms and electricity from the grid was used in Colombia and Honduras as an energy source in processing. Additionally, processing side flows (pulp) and other waste materials were used for heat production. No carbon dioxide emissions were calculated for these bio-based, side-flow energy sources.

Possible anaerobic digestion of biodegradable side flows (pulp) from primary processing was not considered in this study.

2.2.3 Data on green coffee transportation, roasting and package

Transportation data including vehicle types, loads and distances inside the coffee cultivation countries was based on information collected from the case farms and complemented

Table 3 General assumptions in data inventory

General assumptions		Data source
Density of coffee plants	4500/ha	Noponen et al. (2012)
Renewal time period for coffee plants	25 years	Noponen et al. (2012)
Diesel consumption for irrigation	105 kg/ha	Kumar et al. (2012)

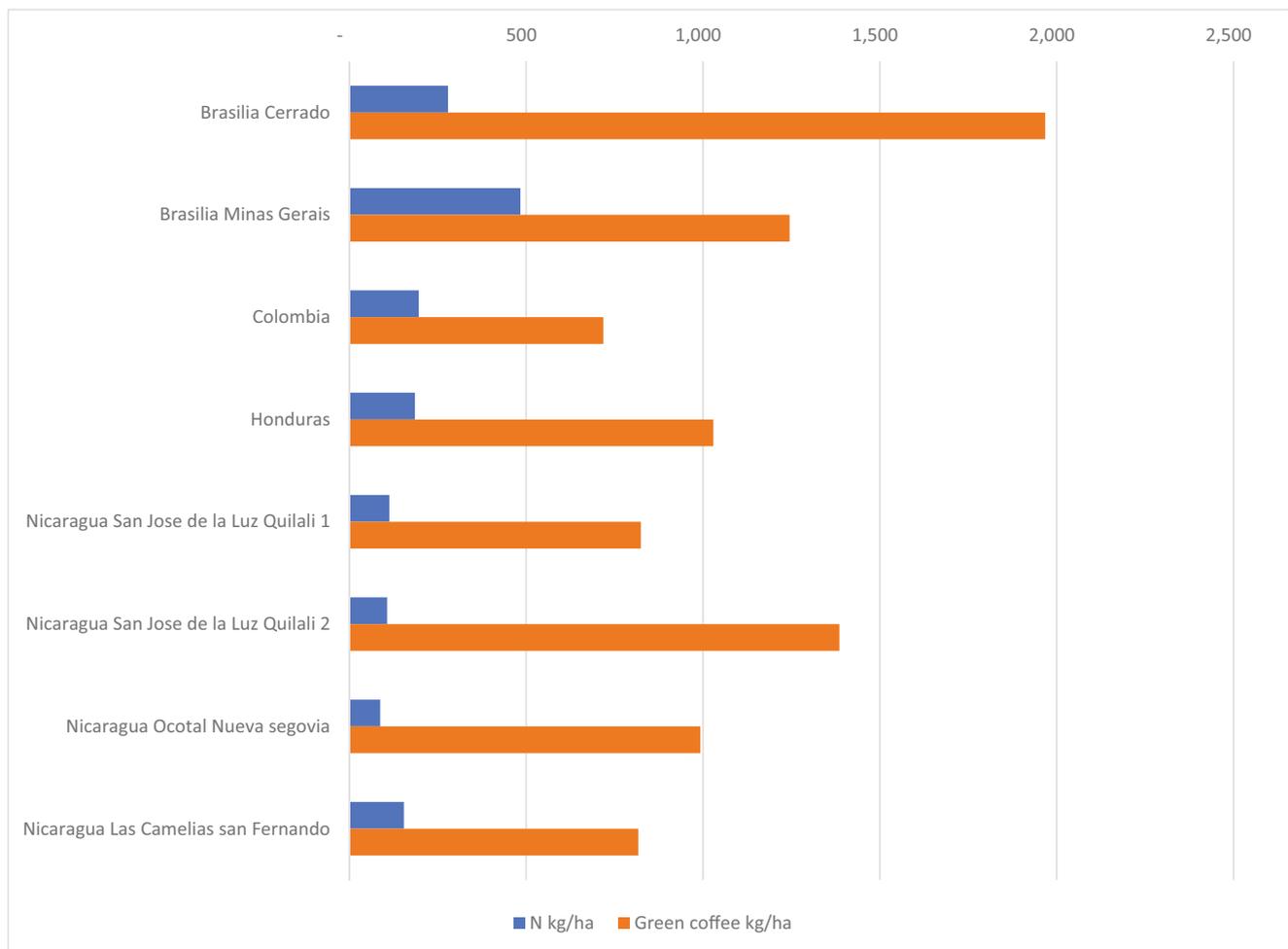


Fig. 2 Nitrogen fertilizing levels and green coffee production yields per hectare for the case farms studied

using data from Google Maps. Inventory data of the transportation from the coffee cultivation countries to the roastery in Finland, including the routes and distances, was calculated according to information from transportation companies for the different routes.

Information about coffee the roasting process was acquired from Paulig Ltd. for the years 2014–2016. All energy consumption was allocated to the different coffee products according to mass allocation. All inputs used in the roastery were allocated to the coffee, because the side streams contributed to less than 0.5% of the production and the economic value of the side streams was very low.

The coffee roastery uses renewable electricity. The greenhouse gas emission factor for renewable electricity in Finland is very low and amounts to only 15 g CO₂ eq./kWh (LUKE 2018, internal datasets).

The packaging for 500 g of roasted and ground coffee was included in the study. The main raw materials for the coffee package were polyethylene (PE), aluminium and nylon 6. Data on aluminium was obtained from the European Aluminium Association (2018) and the data on polyethylene

and nylon was acquired from Plastics Europe (2018). The energy use in the extrusion, laminating and production of adhesive materials was obtained from the Ecoinvent database, but the emission factors were from the energy suppliers of the packaging production plants.

The water consumption rates according to Plastics Europe (2018) were relatively high and amounted to 31.9 l/kg for HDPE and 22.2 l/kg for LDPE. These amounts probably also include cooling water, which is categorized as in-stream water use and is not considered to have a water scarcity impact (Bayart et al. 2010; Boulay et al. 2018; Kounina et al. 2013). These water consumption rates were, however, used without modifications, as no background data is available which would allow the possible cooling water used to be removed from the dataset and no better data was available.

2.3 Greenhouse gas emissions due to land use change

The greenhouse gas emissions due to changes in land use stem from a change in the carbon stocks on the land. According to the most recent international Life Cycle Assessment

guidelines, such as the Product Environmental Footprint (PEF) (European Commission 2013) and PAS2050 (BSI 2011), greenhouse gas emissions related to changes in land use shall be assessed but need to be kept separate when communicating the results.

Greenhouse gas emissions due to land use changes in coffee cultivation were assessed according to the PEF (European Commission 2018) and PAS 2050:2011 (BSI 2011) and the supplementary document PAS2050-1:2012 (BSI 2012) on a national level as previous land use unknown. Changes in four land use categories were considered, namely cropland and perennial crops, grassland and forest land. The carbon stock factors are from IPCC (IPCC 2006), FAO's Global Forest Resource Assessment (2010) and European Commission (2010). Worst case of weighted and normal average has been used as required in PAS2050.

The calculations were made using Direct Land Use Change Assessment Tool (Version 2013.1) by Blonk Consultants. The tool was updated with most recent data during the time of the study regarding the land use area of all crops, grassland and forest areas (1993–2015) from FAOSTAT (2018), and the replacement of other land use to cultivation area of coffee was assumed accordingly. The land use changes were estimated using a 3 years' average for the three most recent years (2013–2015) and a 3-year average from 20 years back (1993–1995).

In Brazil, the cultivation area had increased in the observed period only modestly. In fact, for more than the last 10 years, the cultivation area has decreased, see Fig. 3. Thus, the additional greenhouse gas emissions were only 0.04 tCO₂-eq./ha/year.

In Nicaragua, the cultivation area had increased significantly at the beginning of the observed period (see Fig. 4). However, in the last 10 years, there has not been a significant increase, only annual variation. The additional greenhouse gas emission from land use changes was large and amounted to 5.2 tCO₂-eq./ha/year.

In Honduras, the cultivation area had increased significantly and pretty constantly in the observed period (see Fig. 5). The emissions from land use change were though not so high as in Nicaragua as part of the increased area came from land used for annual crops in addition to forest areas. However, the additional greenhouse gas emissions from changes in land use were still large at 3.1 tCO₂-eq./ha/year.

In Colombia instead, the cultivation area has decreased in the past 20 years, even though it has been increasing in the last few years, and thus, no emissions related to land use changes were allocated to coffee cultivation (see Fig. 6).

2.4 Coffee making and consumption

Making coffee at home included water use, coffee beans, filters (if used) and electricity used in two types of coffee machines; traditional coffee machine with a filter (drip-brew) and a French press (see inventory data in Supplementary material Table S2). For drip-brewing coffee makers, the average standby time (plate kept hot) is assumed to be 37 min (Humbert et al. 2009). There is a lack of information on liquid food waste in households in Finland, but according to a single survey by Luke/Hanna Hartikainen (personal comm.), as a baseline, it is assumed that on average, 1.25% of coffee is wasted by the consumer.

Some scenarios with different consumer behaviour at home were calculated (Supplementary material Table S3). For drip-brewed coffee, scenarios with increasing heating standby time up to 120 min instead of 37 min were calculated. For using a French press, some extra hot water may be used to warm up the French press and “pot heating” scenarios included this option. In the baseline scenario, food-waste was assumed to be 1.25%. However, much higher food waste assumptions are made in the literature (Chayer and Kicak 2015). Increasing the food waste rates up to 30% was calculated for both coffee machines.

Coffee making using automatic office coffee machines was also calculated. A comparison of automatic office

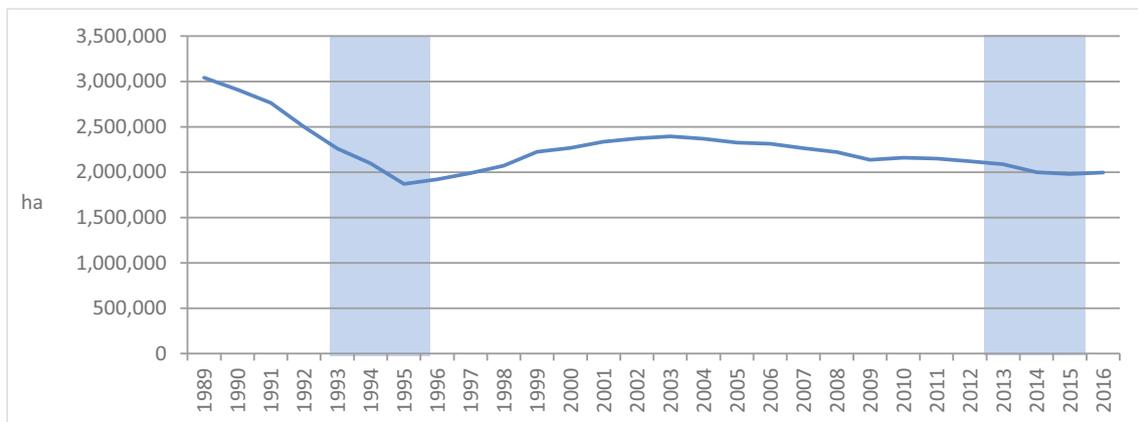


Fig. 3 Coffee cultivation area in Brazil from 1989 to 2016 (source: FAOSTAT 2018)

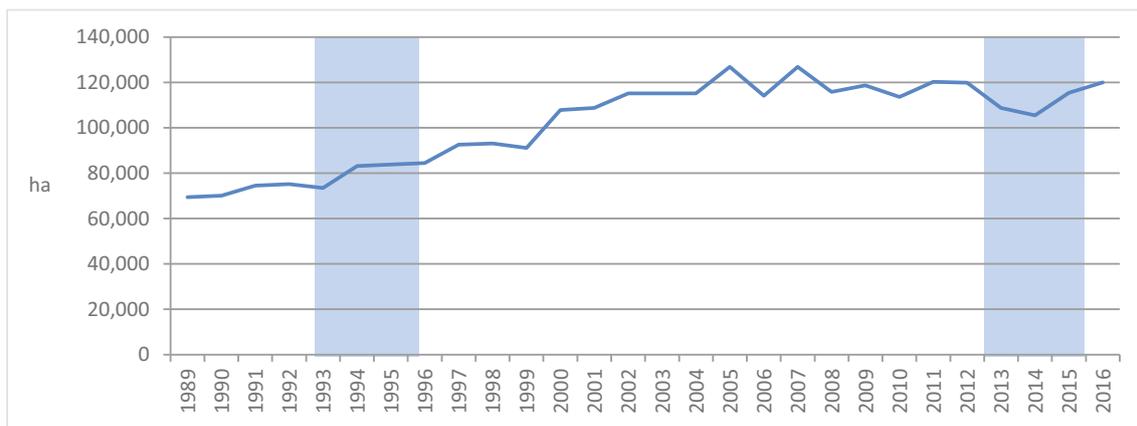


Fig. 4 Coffee cultivation area in Nicaragua from 1989 to 2016 (source: FAOSTAT 2018)

coffee machines included three types of machines from two companies: two professional automatic coffee machines with a fridge and one without a fridge. Data on the consumption of coffee beans, energy, water and cleaning detergents was obtained from the manufacturing companies. Inventory data for basic black coffee is presented in Table S2 in the supplementary material. Coffee drinks with milk and sugar were also studied. Three scenarios were formulated:

- 1 Coffee with milk and sugar made by using a drip-brew coffee machine, French press and two automatic coffee machines with a fridge
- 2 Latte made by two automatic coffee machines with a fridge
- 3 Cappuccino made by two automatic coffee machines with a fridge

The inventory data for these coffee drink options is presented in Table 4. In terms of the water scarcity impact, it was assumed that Finnish milk (Usva et al. 2019) and Danish sugar (EcoInvent) were used.

2.5 Dish washing and waste management

Dish washing data is presented in Table S2. Different usage times have been presented in different studies (Lighthart and Ansems 2007; Refiller 2018). In this study, the usage time for a mug was assumed to be 3000 times, according to Lighthart and Ansems (2007).

In the case of drip-brew coffee, the coffee grounds and the paper filter are disposed of after use. It is assumed that in Finland, 32% of kitchen biowaste is collected separately and 68% together with mixed waste. Mixed waste is incinerated and separately collected biowaste is managed by composting (50%) or used in biogas reactors (50%) (Silvennoinen et al. 2017).

The end-of-life scenario for package waste management was incineration, which was assumed to take place at the Vantaa Energia plant in the capital area of Finland. The energy recovery has been taken into account as recommended in the PEF instructions. The heat values for polyethylene (43 MJ/kg) and nylon (32 MJ/kg) (Shibasaki 2017; Tsiamis et al. 2016; Walters et al. 2000) were used to assess the amount of energy. According to personal communications with Laura Ikäheimo

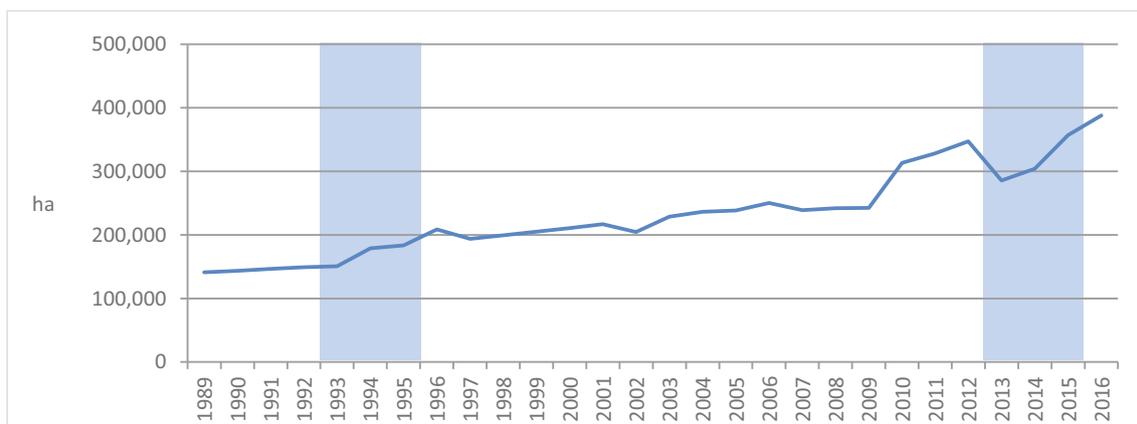


Fig. 5 Coffee cultivation area in Honduras from 1989 to 2016 (source: FAOSTAT 2018)

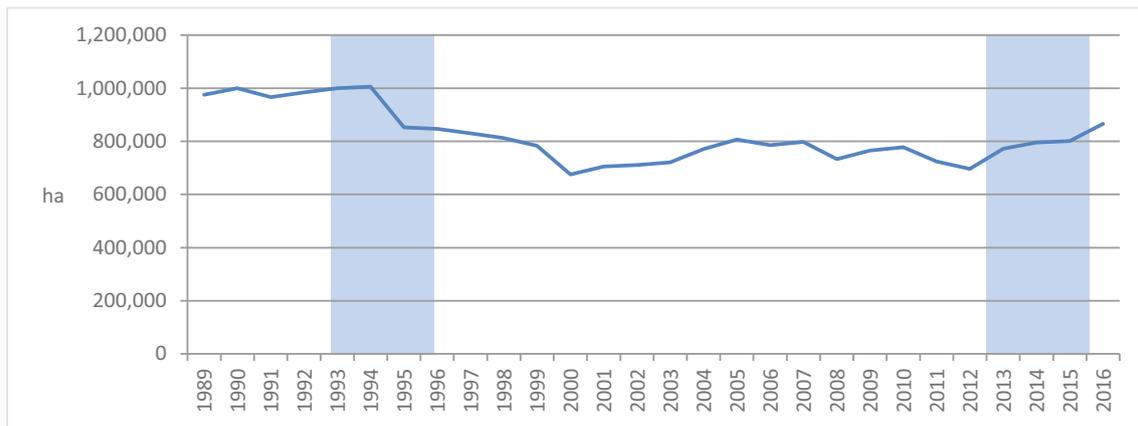


Fig. 6 Coffee cultivation area in Colombia from 1989 to 2016 (source: FAOSTAT 2018)

and Kalle Patomeri from Vantaan Energia, the recovery rate is 88%. It was assumed that the replaced energy consisted of:

- 37.5% heat energy obtained from coal
- 37.5% obtained from natural gas
- 25% average Finnish electric energy.

The amount of produced carbon dioxide emissions was calculated based on the carbon contents of nylon and polyethylene.

3 Results

3.1 Overview

The carbon footprint results for 1 l of drip-brewed black coffee without sugar originating from eight farms were calculated and the characterization was applied according to the IPCC 2013 (Myhre et al. 2013). The results are presented in Fig. 7 and they vary from 0.27 to 0.70 kg CO₂ eq/l coffee. Coffee cultivation accounts for the vast majority of the impacts and

the significance of processing, packaging and transportation are negligible. The consumer stage also makes a significant contribution to the impacts of coffee.

The water scarcity footprint of 1 l of drip-brewed black coffee without sugar is illustrated in Fig. 8. Irrigation was the largest contributor to the results. For this reason, the irrigated coffee chains are presented separately from the non-irrigated one. The total amount of water consumed in the non-irrigated systems studied was about 8 l, and in irrigated systems, it came to 60 and 110 l per litre coffee, corresponding a water scarcity impact about 0.02 m³ eq/litre coffee for non-irrigated systems and from 0.15 to 0.27 m³ eq/litre coffee for irrigated systems.

3.2 Coffee production

The fertilization rate was the largest contributor to the carbon footprint (Fig. 7). Fertilizer manufacturing has a significant carbon footprint; in addition, nutrient use causes direct nitrous oxide (N₂O) emissions from soils. This can be seen especially in the carbon footprints of Brazil/Minas Gerais and Colombia

Table 4 Ingredients of different coffee drinks

		Volume of ready drink, ml	Amount of coffee beans, g/cup	Amount of water, ml/cup	Amount of milk, ml/cup	Amount of sugar, if used g/cup
Automatic coffee machines 1	Black coffee	140	12.5	150	0	4
	Coffee with milk	140	12.5	110	40	4
	Cappuccino ²	140	11	50	60	4
	Latte ²	140	11	40	100	4
Home (drip-brew and French press)	Black coffee	140	9.1	140	0	4
	Coffee with milk	140	6.5	100	40	4

¹ 10-ml water/cup wasted in the process

² Milk foam produced out of milk, increasing the volume of ready drink

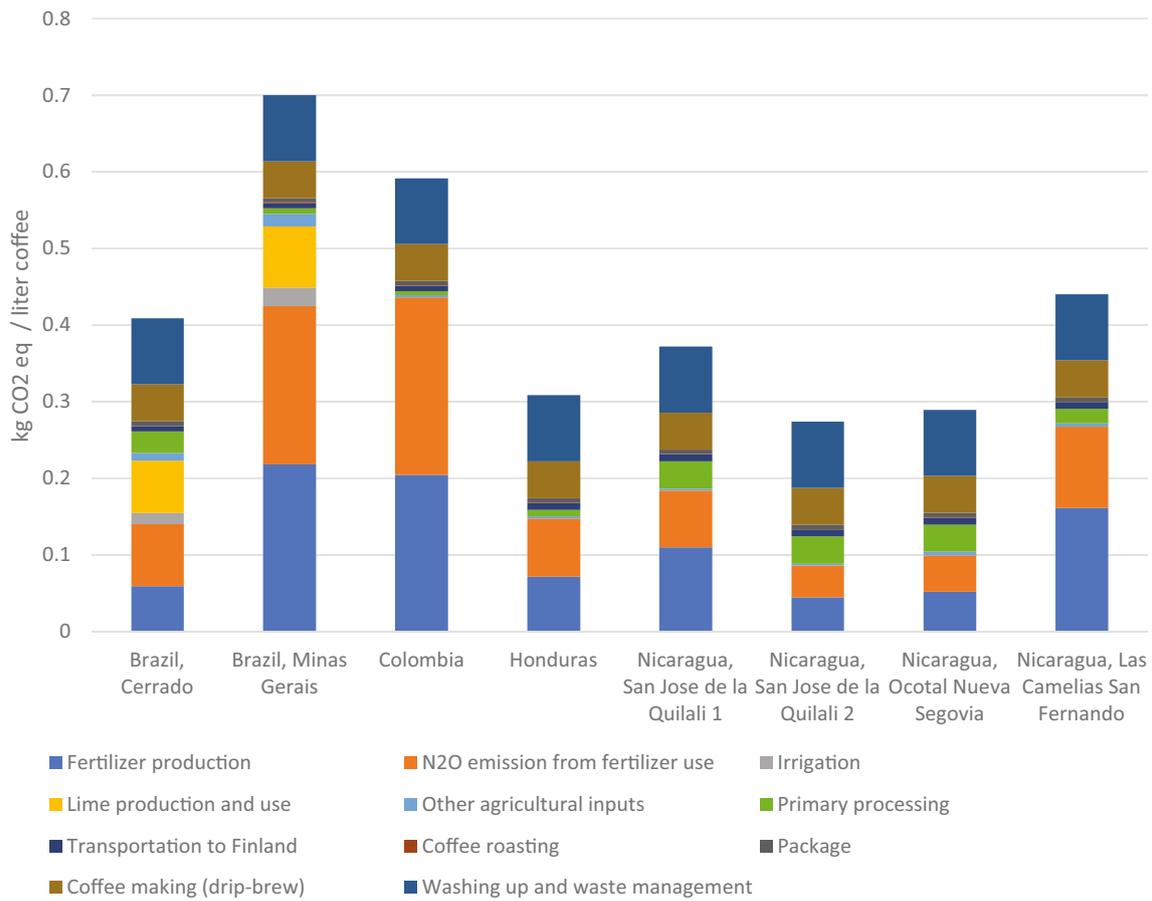


Fig. 7 Carbon footprints in kg CO₂ eq per 1-l coffee

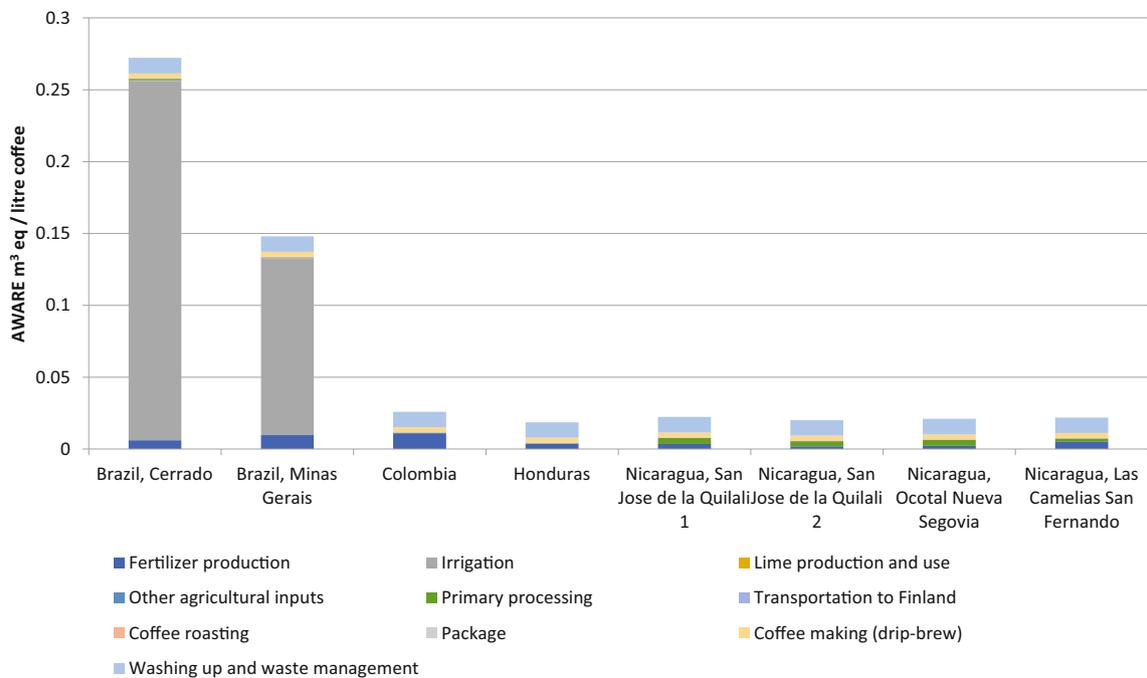


Fig. 8 Water scarcity impact (AWARE) in m³ eq per 1 l of coffee

farms having high N-fertilization rate compared with the yield.

A noticeable CO₂ emission source is liming, especially in the Brazil Cerrado and Minas Gerais areas where high levels of lime are applied annually (see Section 2.2.2). Other agricultural inputs include fuel in cultivation, if used, seedling production and pesticide production. The farms in Brazil had the highest impact on “other agricultural inputs” due to the higher number of machines and the diesel consumption compared with the other case farms.

The climate and water scarcity impacts of coffee roasting were less than 1% of the total impact of the value chain. The carbon footprint of packaging is less than 2% and the water scarcity impact is less than 0.5% of the total impact of the value chain. The reductions of emission in the end-of-life amounted to 3% of total carbon footprint, taking into account credits for obtained energy and emitted amounts of carbon dioxide from plastics incineration.

The water scarcity impact is naturally higher for the irrigating farms in Brazil (Fig. 8). The amount of irrigation water exceeds all other water consumption. Fertilizer manufacturing and wet processes in primary processing comprise most of the impacts in addition to irrigation.

3.3 Carbon footprint from land use change

Carbon footprints due to land use changes are presented on a national level for Nicaragua, Honduras, Colombia and Brazil in Fig. 9. In Colombia, in the observed period, no land use changes had occurred. In Brazil, they were very small at about 0.5%. For Honduran and Nicaraguan green coffee, the emissions from land use changes contributed 60–75% of the total carbon footprint.

3.4 Coffee making and consumption

The climate and water scarcity impacts of coffee making and consumption both in the office and at home per 1 l of black coffee without sugar are presented in Fig. 10. Green coffee from the Colombian case farm is selected here to represent the primary production.

When increasing the food waste rate to 30%, the total carbon footprint of 1 l of consumed coffee increases by about 27%. A scenario with 120 min of stand-by instead of 37 min increases the total carbon footprint of drip-brewed coffee by about 4%. The extra hot water to heat the French press increases the total impact by about 3% as well.

The office coffee machines varied only slightly from each other. The automatic coffee machine models with a fridge had higher electricity consumption which resulted in a higher carbon footprint in the coffee-making stage. The carbon footprints of drip-brewed coffee and French press coffee for consumers at home are lower due to smaller amount of ground coffee consumed per litre of coffee (see Table 4). The electricity consumption for dish washing accounted for the majority of the carbon footprint, and the water consumption for dish washing accounted for the majority of water scarcity impact in the consumer stage. The consumer scenario results are presented in detail in Figure S1 in the supplementary material.

The results of coffee drinks with milk and sugar are presented in Figures S2 and S3 in the supplementary material. Coffee drinks with milk have a higher carbon footprint because milk itself has a higher impact, and also because, in the case of automatic coffee machines, more coffee beans are used for the coffee drinks with milk, especially latte and cappuccino. In terms of the water scarcity impact, it is lower for Finnish milk than for coffee, and therefore, the homemade coffee drinks without milk, but more coffee instead, have higher water scarcity impacts than coffee drinks with milk.

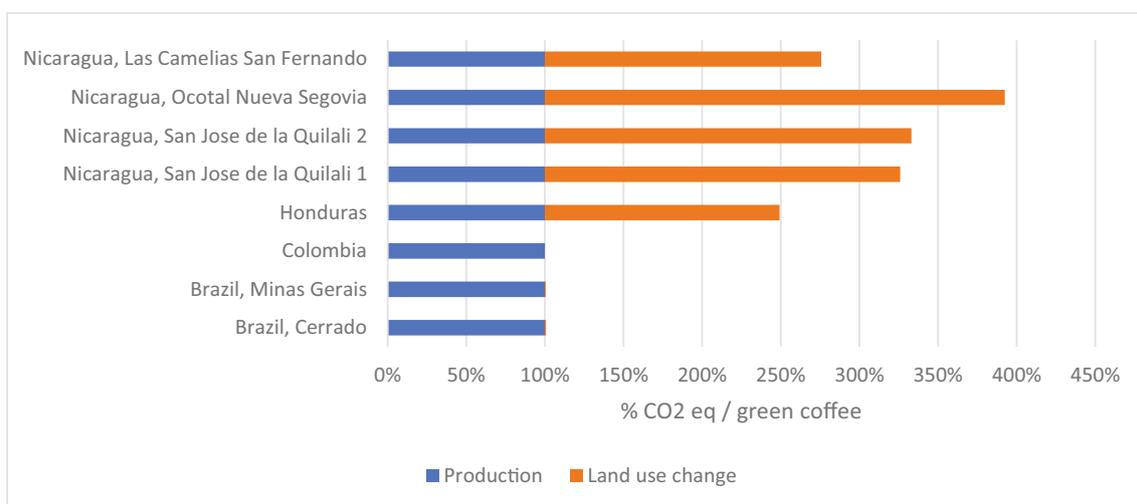


Fig. 9 Relative share of the carbon footprint of green coffee (kg CO₂ eq/kg green coffee) in Vuosaari harbour in Finland, including land use change

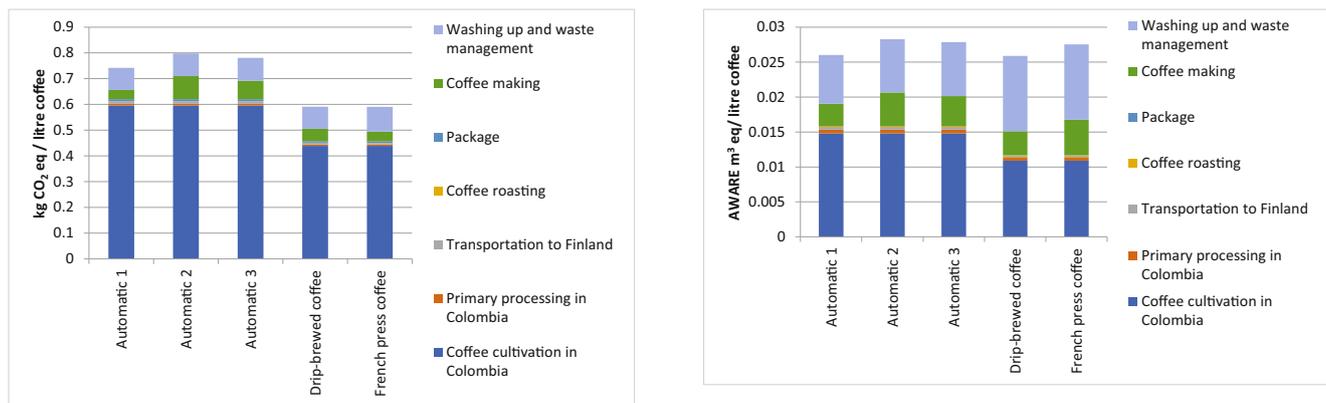


Fig. 10 Carbon footprint (kg CO₂ eq) and water scarcity impact (AWARE m³ eq) of 1 l of coffee prepared by three different automatic office coffee machines (automatic 1 = without fridge, automatic 2 and 3 = with fridge), one drip-brewing machine and one French press

4 Discussion

4.1 Hotspots of the coffee chain

Primary production is the hotspot of the coffee chain. In the study by Killian et al. (Killian et al. 2013), the share of farming was 1.02 kg (21%) CO₂ eq/kg green coffee. In our study the climate impact of farming varied from 1.1 to 6.6 kg (from 32 to 78%), indicating also a lot of variation between farming systems.

In contrast to many previous papers (e.g. Büsser and Jungbluth 2009; Hicks 2017; Humbert et al. 2009; Killian et al. 2013; Salomone 2003), the contribution of the consumption stage to the carbon footprint was smaller in this study. According to Killian et al. (Killian et al. 2013), the share of consumption was 2.15 kg (45%) CO₂ eq/kg of green coffee, and in our study, the consumption stage was 1.6 kg (from 19 to 49%). The differences concerning the consumption stage are mostly caused by the difference in electricity production types between Finland and other countries in Europe. In 2015, as much as 79% of the electricity produced in Finland was produced by renewables and nuclear. The share of renewables was 45% (Official Statistics of Finland 2016). For example, the EU in 2016, renewable electricity was 29% and nuclear energy sources contributed 26% of all gross electricity generation (European Environment Agency (2018)).

Transport and retail packaging were of minor importance and the studies by Büsser and Jungbluth (2009) support that. The roastery used renewable electricity and waste-derived biogas partly for heat production. Due to very low emission rates of these energy sources, the share of the roastery is only 0.1–0.2% of the carbon footprint for roasted and packed coffee.

Irrigation dominates the water scarcity impact results. In the two irrigating farms, the irrigation was 750 and 2425 m³/ha (602 and 1233 l/kg green coffee, respectively). Pfister and Bayer (2014) assessed the irrigation level for Brazilian coffee 1104 m³/ha. We calculated the total amount of water consumed per litre coffee about 8 l for non-irrigated and 60 and 110 l for irrigated systems. Humbert et al. (2009) calculated

the water consumption in the whole coffee chain (drip-brew) 40 to 400 l of non-turbined water per litre of coffee, depending on whether the coffee cherries were irrigated or not.

Coltro et al. (2006) studied water consumption for coffee processing. The range in their study was from 0.072 to 60 l water per kg of green coffee and the weighted average was 11.437 l. In our study, the range is from 0 (no wet process) to up to 6.235 l per kg of green coffee.

4.2 Land use change

As explained in Section 2.2.2, especially in Nicaragua and Honduras, the coffee cultivation area has grown strongly causing a significant increase in the total carbon footprint of Nicaraguan and Honduran coffee.

In Brazil, the cultivation area had increased in the observed period only modestly. In the next 2 years, if the cultivation area does not increase again, there will not be any additional emissions from land use change to be considered.

In Nicaragua, the cultivation area had increased significantly at the beginning of the observed period, but in the last 10 years, there has not been a significant increase. For now, the additional greenhouse gas emissions from land use changes are large, but in the next years, if the cultivation area does not expand again, the additional greenhouse gas emissions will decrease.

In Honduras, the cultivation area has increased steadily and significantly throughout the observed period. In the last few years, the increase has accelerated even further, and if continues, in the future, an even larger share of greenhouse gas emissions should be allocated to coffee cultivation.

In Colombia instead, no emissions related to land use changes are allocated to coffee cultivation. However, in the last 5 years, the area has been increasing, and thus, if the trend continues, in few years' time, there may be significant additional emissions to be considered.

In addition to the climate impact, land use changes may also have their own implications on the water balance in the area. Both changes in the surface runoff and river discharge as

well as water quality degradation are common consequences when natural vegetation is changed into an agricultural land (Foley et al. 2005).

4.3 Further research needs

Only the climate and water scarcity impacts were the focus of this study. In the literature, it has been recommended concerning the milling process that the focus should be specifically on the proper management of wastewater (Killian et al. 2013). There may be unstudied methane emissions related to wastewater and sludge treatment, and eutrophication impact related to wastewater treatment and cultivation should also be studied further. Biodiversity loss is globally one of the most serious environmental problems and in terms of coffee, biodiversity impact especially due to land use change should be studied in the future. In addition to environmental impacts, social issues should also be incorporated as part of the overall system management (Adams and Ghaly 2007).

In this study, we recorded variation between the farms. More representative samples are needed if one wants to study the average environmental impacts of coffee production in each of the producer countries. The variation between farms also means that there are still many opportunities to optimize coffee production. Improving the processes in cultivation and fertilization is key to achieve lower GHG emissions.

As explained in Section 1, nitrogen use is reported as the most important factor in the coffee chain in terms of the carbon footprint. In this study, the share of fertilizers (incl. fertilizer production and emissions from use) contributed altogether 60 to 99% of the total carbon footprint in the farming stage. However, there was notable variation between the case farms.

Both the Brazil/Minas Gerais and Colombian case farms applied relatively high levels of nitrogen fertilizers compared with the yield and in general, and there was a large variation in N fertilization (see Section 2.2.2). Coltro et al. (2006) concluded that although the use of fertilizers and pesticides depends on the specific needs of each agricultural field; these great differences evidence a clear opportunity for the reduction of these inputs. A sensitivity analysis for the carbon footprint with fertilization rates of -20% and $+20\%$ is presented in Supplementary S3.

In this study, we saw that irrigation dominates the water scarcity impact results. Due to the high water consumption on irrigated farms, optimization of farming practices is needed. In Brazil, the irrigated area was 10% of the total coffee plantation area in 2007 and provided 22% of the yield (de Assis et al. 2014). In a study by de Assis et al. (de Assis et al. 2014), irrigation increased the mean yield of coffee by almost 50% compared with non-irrigated cultivation (plant density 10,000 or 20,000 plants per hectare). However, Eriyagama et al. (Eriyagama et al. 2014) concluded that the coffee-producing countries Brazil, Nicaragua, Colombia and Honduras have higher water consumption (if irrigated) and slightly lower yields than they potentially could by implementing better farming practices.

All Central American production sites, Nicaragua, Honduras and Colombia, apply wet processing but there are some differences in the amount of water: the Nicaragua/San Jose de la Quilali 1 farm used 3.3 l and the Colombian farm used 2 l per kg of green coffee during the wet process. This indicates differences in the process technologies applied on these case sites.

However, actions to reduce climate and water scarcity impacts (at least) should be executed side by side to avoid negative side effects.

Only few water scarcity impact assessment studies have been executed before. Irrigation dominates the results, but mostly modelled irrigation data is available, no primary data. In the future, more primary data on the actual amount of irrigation water should be collected.

In terms of water scarcity impact, it might be important to find out the origin of some inputs; i.e., we found out that fertilizer production had an relatively high water scarcity impact. The manufacturing country of the fertilizers was not known and therefore, global characterization factors were used for fertilizer production. All four countries concerned in this study: Brazil, Honduras, Colombia and Nicaragua, have much more abundant water resources than the world average (see Table 1). If the fertilizer manufacturing area were known to be some of those countries, the impact would have been lower.

5 Conclusions

In this study, carbon footprints and water scarcity impacts were calculated for coffee originating eight farms in South and Middle America and roasted and consumed in Finland. The carbon footprint results vary from 0.27 to 0.70 kg CO₂ eq/l coffee. The water scarcity footprint of 1 l of drip-brewed black coffee without sugar is 0.02 m³ eq/l coffee for non-irrigated systems and from 0.15 to 0.27 m³ eq/l coffee for irrigated systems. The total amount of water consumed in the non-irrigated systems studied was about 8 l, and in irrigated systems, it came to 60 and 110 l.

In this study, primary data from the coffee production chain was obtained. Even though the number of case farms was low, conclusions on the most important stages in the value chain may be drawn and indications of possible mitigation actions are given.

As concluded in previous studies, coffee cultivation and consumption are the hotspots in the coffee value chain in terms of the carbon footprint. Irrigation was the largest contributor to the water scarcity impact. Thus, cultivation is also the most critical for improving the environmental performance of the production chain. In order to optimize the environmental sustainability of coffee production system, roasters and retailers should engage their suppliers to manage their GHG emissions, for example, by improving their management practices. The water scarcity impact is highly dependent on the rate of irrigation, but irrigation may also lead to better yields and more efficient utilization of nitrogen. Optimization is needed at the farm level to balance the amount of agricultural inputs,

especially irrigation water and fertilization in regard to the yield potential of the production to avoid excess use of inputs.

Consumers also have a role in the life cycle of coffee and should take responsibility and minimize their own impacts. Coffee is a discretionary product, and it should be considered if one can consume less of it. If consuming coffee, this study indicates that the most important issue for a consumer is to avoid wasting coffee. Consumers should also minimize water consumption during washing and rinsing coffee mugs and de-canters. Increasing knowledge on sustainability aspects of coffee enables improvements in production. Consumers should also start purchasing more sustainably, when options are available.

Acknowledgements Open access funding provided by Natural Resources Institute Finland (LUKE). The authors would like to thank especially Seija Säynevirta, Timo Allen and Kati Randell for sharing their expertise, data collection and supporting the work in many ways.

Funding information This study has been funded by Paulig Ltd and Natural Resources Institute Finland.

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