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REGULAR ARTICLE

Carbon and water footprints in Brazilian coffee plantations - the spatial and temporal distribution

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ABSTRACT

The future of many coffee growing regions, such as Brazil, depends on strategies to allow the minimization of the negative impacts of climate change. Still the own contribution of coffee cultivation for global warming is largely unknown. Water and carbon footprints are concepts that indicate the potential negative impact of a specific product, underlining which part of the process is the major responsible for it. In this context, the objective of this study was to quantify and spatialize the water and carbon footprints from coffee crop in different regions of Brazil, and to find the proportional weight of coffee production in the total emission of CO_2 and water consumption in the context of Brazilian agriculture. For this end, water and carbon footprints were estimated and spatialized for Brazilian regions along 10 productive seasons (from 2004/2005 to 2014/2015), based on data of plantation area (ha) and coffee production (tons of beans). It is concluded that the estimates of annual carbon and water footprints were 19.791 million t CO_2-equivalent and 49,284 million m^3 of water, with higher values from the Southeast region. This corresponded to a moderate (ca. 5%) value for the emissions of greenhouse gases, but a relevant water footprint in the context of Brazilian agriculture.

Keywords: Carbon and water footprint; Climate changes; Coffee bean production

INTRODUCTION

Climate changes and global warming estimates for the present century (IPCC, 2013; 2014), raise important uncertainties related to future sustainability of the coffee crop production, based on *Coffea arabica* L. (Arabica coffee) and *Coffea canephora* Pierre ex A. Froehner (Robusta coffee) that account together for approximately 99% of world coffee production. Recent works have been shown that the estimated increase in air [CO_2] could have a positive impact on the coffee plants, since it strengthens photosynthetic performance (Ramalho et al., 2013; DaMatta et al., 2016). Furthermore, enhanced air [CO_2] can significantly mitigate the predicted physiological heat impacts, as regards leaf mineral balance (Martins et al., 2014), the triggering of defence mechanisms and gene expression patterns (Martins et al., 2016; Rodrigues et al., 2016), and, ultimately, contributing to preserve coffee bean quality (Ramalho et al., 2018). Nevertheless, several reports predicted important reductions of suitable areas, and increases in pest incidence, particularly as concerns *Coffea arabica* L., largely related to the increase of average air temperature, intra-seasonal variability of temperature and water availability (Bunn et al., 2015; Craparo et al., 2015; Magrach and Ghazoul, 2015; Martins et al., 2017), with impact on the livelihoods of millions of small householders. Although, elevated air [CO_2] has the ability to soften the predicted impacts of supra-optimal temperatures, it seems indisputable that impacts from climate changes are already happening (Craparo et al., 2015; van der Vossen et al., 2015), with growing socioeconomic impacts caused by progressive and extreme climatic events, mainly reported on Central and South America. Moreover, the future scenarios of climate changes show a reduction in areas with annual mean rainfall effective for coffee

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production (Chapagain and Hoekstra, 2007; Eriyagama et al., 2014). These findings reinforces the need for the implementation of mitigation and adaptation strategies, aiming at decrease the impact of climate changes and global warming on the coffee production and quality (Rikxoort et al., 2014; Rahn et al., 2014; Bunn et al., 2015; Dubberstein et al., 2018). These strategies of mitigation and adaptation to climatic vulnerability must include the increase of C-sequestration, decreasing carbon footprint, and of water footprint required to grow coffee trees and to produce coffee beans (Läderach et al., 2010; Rikxoort et al., 2014; Rahn et al., 2014).

There are few reports about strategies to produce coffee under influence of climatic stresses, whereas considering as well the need to decrease its carbon and water footprint. Some results show that cropping coffee under shaded conditions may reduce up to 56% of carbon footprint (Hergoualc'h et al., 2012). Furthermore, this mitigation strategy promoted increases in carbon stock up to 32 t CO_2-eq ha^{-1} (Soto-Pinto et al., 2010; Hergoualc'h et al., 2012). Furthermore, the use of agroforestry systems for coffee cultivation can turn a coffee area from a carbon emitter to a carbon sequestration (Andrade et al. 2014). Carbon stock in green biomass (coffee tree) has not been included in carbon footprint of the product. However, spatial estimates indicates that its quantification may reduce 92% of carbon footprint, revealing the mitigation potential of the coffee plantation itself (Martins et al., 2015).

Disturbing signs are also attributed to water footprint in coffee production, since it is estimated that one single coffee cup requires the use of near 140 litters of water, being the most part attributed to growing the trees. This fact unveils the impact of bean processing over the water footprint, since only 0.4% of the footprint comes from coffee processing (Chapagain and Hoekstra, 2007). Currently, the initial estimates suggest that between 8.2 and 26.3 cubic meters of water are used in the production of 1 kilogram of green coffee; varying between regions, species and cultivation systems (Chapagain and Hoekstra, 2007; Eriyagama et al., 2014).

Overall, studies involving carbon and water footprints due to coffee production showed that most efforts are being developed in regions between 0°N and 30°N of latitude, especially for countries of Central America, Africa and part of Asia, with only a few reports for regions between 0°S and 30°S of latitude, where Brazil is located. Ironically, Brazil stands for near 30% of world coffee production, with annual exports yielding *ca*. 5600 million USD (ICO, 2016). This numbers indicate a dimensions of the socioeconomic important of coffee in Brazil, therefore, any modification in the climatic aptitude expected for the regions between 0°S and 30°S of latitude (Bunn et al., 2015; Magrach and Ghazoul, 2015) would cause large impacts in coffee production.

The objective of this study was (i) to accurately estimate and spatialize the water and carbon footprints due to the coffee crop from different regions of Brazil along ten years; and (ii) to quantify the proportional responsibility of coffee production in the total emission of CO_2 and water consumption of Brazilian agriculture.

MATERIAL AND METHODS

Case study and time-series. This study was performed considering Brazil (area: 8,515,767.049 km^2), located at latitude and longitude of 10° S and 55° W. The geographic stratification of the area planted with coffee trees (ha) was carried out based on data of plantation area (ha) and coffee production (tons of beans), from 10 productive cycles of the species *Coffea arabica* L. and *Coffea canephora* Pierre ex A. Froehner, from 2004/2005 to 2014/2015, based on the agricultural census (Table 1).

Calculation of carbon and water footprints. The carbon footprint (t CO_2-eq) was calculated using the Cool Farm Tool (CFT) (Hillier et al., 2011), based on the coefficient determined for coffee produced (beans) in commercial unshaded monocultures (Rikxoort et al., 2014). This coefficient is between 6.2 and 9.0 t CO_2-eq t^{-1} of produced coffee beans, therefore, an average of 7.6 t CO_2-eq t^{-1} of coffee beans was used for standardization. The water footprint (m^3) of green coffee was calculated using the coefficient based in virtual water content, representing the volume of water required to produce green coffee. The most suitable coefficient for Brazil is 18,925 m^3 t^{-1} (water volume per green coffee beans mass, processed through the wet method) (Chapagain and Hoekstra, 2007). Data of 10 consecutive years of cultivation were used to calculate carbon and water footprints for

Table 1: Summary of the climatic means of coffee producing regions in Brazil[1]

State	Regions	Altitude[2]	Rainfall[3]	Temperature[4]
Minas Gerais	South	950	1,500	22.0 a 24.0
	Cerrado	800	1,400	24.0
	Chapada	960	1,000	24.3
	Montanhas	600 to 1,100	1,220	14.6 to 21.8
Espírito Santo	Mountains	700 to 1,100	1,341	17.0 to 22.0
	Conilon	100 to 300	1,100	24.0
São Paulo	Mogiana	900 to 1,000	1,523	18.0 to 20.0
	Centro-Oeste	200 to 600	1,350	20.7
Paraná	Norteh"Pioneiro"	900	1,300	21.0
	Arenito	350	1,246	21.5
Bahia	Cerrado	400 to 850	1,120	24.5
	Chapada	100 to 200	1,261	24.2
Rondônia	Rondônia	200	1,500	24.6 to 25.6

[1]IBGE, 2015; [2]Altitude: m; [3]Rainfall: mm; [4]Temperature: °C.

coffee production systems, because previous studies have reported this as representing the time of maximum carbon accumulation in coffee plants (Rodrigues et al., 2000).

Spatialization and data analysis. The data of carbon water footprints were grouped for regions of the Brazil (South, South East, Central West, Northeast and North) and statistically analyzed for normality verification (Kolmogorov-Smirnov, level of significance of 0.05) through the Genes program (Cruz, 2013). All spatialization representations were performed with the program ArcGIS® (version 10.2, ESRITM).

RESULTS AND DISCUSSION

The higher estimates for carbon footprint (CFP) and water footprint (WFP) in coffee monocultures (*C. arabica* and *C. canephora*) were found in Southeast region of Brazil and the lower estimates of CFP and WFP were obtained in the Center-West region (Fig 1, Fig 2; Table 2).

This differences in the distribution was somewhat expected, since the Southeast region presents the largest plantation areas and high level of production of coffee fruits (Table 2) (Martins et al., 2015), while the Center-West region presents agricultural suitability for others species, such as soybean and corn, implicating smaller areas for coffee cultivation. However, coffee production is gradually advancing for central areas of Brazil supported by large scale irrigation schemes, which would increase CFP and WFP of this region in the near future (Fernandes et al., 2012).

The spatial distribution reveals that carbon footprint in Brazil varied between 16 million t CO_2-eq during the 2005/2006 season and 22 million t CO_2-eq during 2010/2011, 2012/2013 and 2013/2014 seasons (Fig 1). Water footprint spatialization varied between 40,000 million m^3 during 2005/2006 season up to 57,000 million m^3 during 2012/2013 season (Fig 2). The lower CFP and WFP from 2005/2006 season may be explained by the implication of climatic adversities occurred in coffee plantations, especially in Southeast region and north of Paraná state (South region), allied to the renovation of coffee plantation in large areas of Southeast region, mainly in Espírito Santo state (Southeast region) and south of Bahia state (Northeast region). Higher estimates CFP and WFP during 2012/2013 season are related to the interaction of favorable climatic events to the exploration of the potential from the areas that were being renovated with new technologies from the early 2000s (Martins et al., 2015).

The estimates indicate that during 10 consecutive years, the coffee plantations in Brazil were responsible for a CFP of near 198 million t CO_2-eq (Table 2), corresponding to only 1.14% of the estimated total of Brazilian emissions of CO_2-eq between 2005 and 2014 (*ca*. 17,429 million Ton CO_2-eq) (SEEG, 2015). Furthermore, coffee CFP had a modest contribution of *ca*. 5% of the total emissions from agriculture activities in Brazil, estimated in 4,030 million

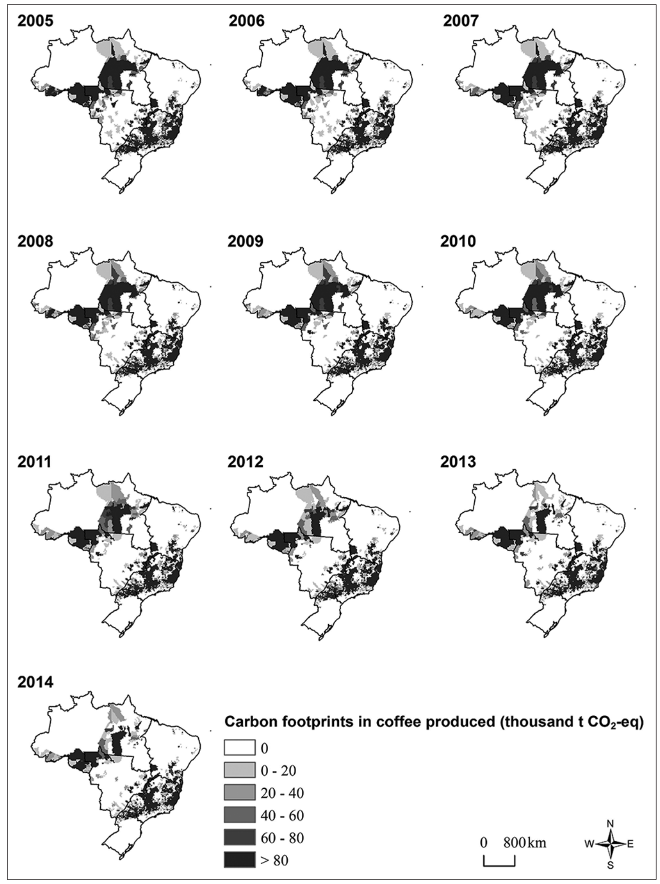

Fig 1. Spatial distribution of Carbon Footprint (million t CO_2-eq) for coffee monoculture (*C. arabica* and *C. canephora*) in Brazil, during 10 production years (from 2004/2005 to 2014/2015). (Universal transverse mercator projection; ellipsoid SIRGAS 2000, zona 24 k).

Table 2: Production of coffee bean (million Ton) and estimate Carbon Footprint (million t CO_2-equivalent) and Water Footprint (x 1000 million m^3) for coffee monoculture (*C. arabica* and *C. canephora*) in regions of Brazil, during 10 production years (from 2004/2005 to 2014/2015)

Region	Coffee beans (million t)	Carbon Footprint (million t CO_2-equivalent)	Water Footprint (x1000 million m^3)
North	1.111	8.443	21.024
Northeast	1.556	11.827	29.450
Central-West	0.313	2.380	5.927
Southeast	21.894	166.394	414.342
South	1.168	8.874	22.097
Total	26.042	197.917	492.840
Standard deviation	0.003	0.020	51
Annual average	2.604	19.792	49.284

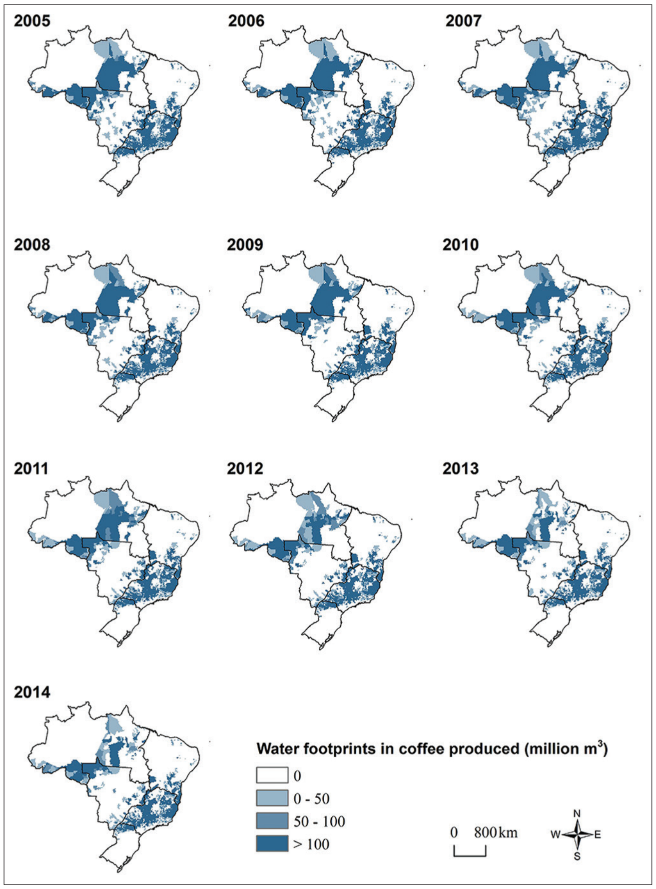

Fig 2. Spatial distribution of Water Footprint (million m³) for coffee monoculture (*C. arabica* and *C. canephora*) in Brazil, during 10 production years (from 2004/2005 to 2014/2015). (Universal transverse mercator projection; ellipsoid SIRGAS 2000, zona 24 k).

Ton CO_2-eq from 2005 to 2015 (SEEG, 2015). Even considering that this coffee CFP values were expressive, the present results do not consider the amount of carbon stocked in the vegetation from the varied cultivation systems of *Coffea* spp., which can mitigate up to 92% of the in-farm carbon footprint from Brazilian coffee (Soto-Pinto et al., 2010; Hergoualc'h et al., 2012; Martins et al., 2015).

Considering the total volume of water used for world crop production regarding the main crops, coffee is responsible to *ca*. 2% WFP (Hoekstra and Chapagain, 2006). However, due to the importance of coffee crop to the tropical are, a larger weight of this crop can expected as concerns the tropical agriculture in general and the Brazilian one in particular. Based on the virtual water consumption coefficient (Chapagain and Hoekstra, 2007), the WFP from Brazilian coffee will reach values close to 49,300 million m^3 per year (Table 2), which is an important WFP as compared to the water consumption by irrigated agriculture in Brazil, which is estimated to represent 23,500 million m^3 per year (ANA, 2017). Nevertheless, although giving a broad idea, are not directly comparable, since the estimate for water consumption by irrigated agriculture in Brazil only includes a small part of the coffee crop. Indeed, recent estimates pointed that irrigated coffee represented only 5.9% of the total area for this crop, with an impact of 6.3% regarding the water spent for the main crops (rice, sugar-cane, corn, bean, soya, wheat) (FGV-EESP, 2016).

Overall, the results for coffee plantations in Brazil indicate higher carbon and water footprints from the Southeast region. C-footprint estimates correspond to only 5% of the emissions of greenhouse gasses. Moreover, 92% of the carbon footprint may be further mitigated if we take into account the carbon sequestration on the biomass of coffee trees. In contrast a large coffee water foodprint can be expected considering its water use in the context of the tropical and Brazilian agriculture (under irrigated and, particularly, non-irrigated cropping systems). Further studies are needed to confirm and actualize these first estimates, considering the growing importance of global irrigated agriculture (including coffee), the predicted scarcity of water resources under a context of climate changes, and the required sustainable management of water resources.

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