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A bitter cup: the estimation of spatial distribution of carbon balance in *Coffea* spp. plantations reveals increased carbon footprint in tropical regions

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ABSTRACT

There is an increasing need to mitigate and adapt the agriculture to climate changes with strategies that synergistically allow minimizing the climate impact over the coffee production and contributing to a decrease of coffee cultivation vulnerability to global warming. In this context, the objective of this study was to analyse the carbon balance in systems of coffee production, which can contribute to information to mitigate climate change, by addressing the cultivation and production of *Coffea* spp. in the tropical regions, such as the Espírito Santo state of the case study (between the meridians 39°38' and 41°50' of western longitude and the parallels 17°52' and 21°19' of southern latitude). For this purpose, data of coffee plantations area (ha), carbon storage, carbon footprint and carbon balance (all in t CO_2-equivalent) were recorded for different tropical regions, from 2001–2012. The estimated parameters indicate that 2 239 476 t CO_2-eq were sequestrated (positive balance) and 10 320 223 t CO_2-eq (negative balance) were emitted. The spatialisation allows estimating that the footprint is reduced in 92% after quantifying the carbon stock in coffee plantations. The carbon balance was negative, with magnitude of 4 815 820 t CO_2-eq, which indicates that the carbon balance in coffee plantations in tropical regions is not enough to compensate the carbon footprint.

Keywords: Arabica and Robusta coffee; global warming; tropical area; carbon stocks

In the last years, the world coffee yield was over 8 million tons of green beans (Arabica and Robusta coffee), originated from around 80 producing countries, mostly from South and Central Americas, as well as from Asia (ICO 2014). It is estimated that the entire value chain of coffee, from cultivation to consumption, would generate a global income of ca. US$ 173 400 million (ICO 2014) and involves between 80 and 100 million people worldwide (Martins et al. 2014, Bunn et al. 2015), justifying its crucial social and economic role for many countries in the tropical region, and also its global economic impact.

In the last decade, there has been an increasing concern of coffee-producing countries, related to the growing frequency of extreme weather events and with the estimates of global warming (IPCC 2014). In fact, the cultivation of coffee at worldwide level is highly dependent of the prevalent weather conditions, namely of adequate temperatures and water availability (Ramalho et al. 2013, Martins et al. 2014,

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Bunn et al. 2015, Ghini et al. 2015). In this context, a recent global study indicates that South America, Central America, Africa and Asia and other regions of the world at tropical latitudes, may suffer significant changes in agro-climatic zoning and severe loss of areas suitable for coffee cultivation in the future due to, among other factors, rising temperatures and the intra-seasonal variability of temperatures (Bunn et al. 2015, Craparo et al. 2015).

There is a growing need for approaches that might help farmers to adapt the coffee cultivation to the predicted climate change and, synergistically, promote reduction of the own coffee crop contribution to the global warming; the adoption of actions occur in other coffee producing regions in the world (Läderach et al. 2010, Rahn et al. 2014). Special attention should converge to actions aimed at increasing carbon sequestration or decreasing coffee carbon footprint. This is justified first by the fact that despite the coffee cultivation being affected by climate change, the change of land use in recent years has had a large contribution to the amount of emissions of greenhouse gases (Tchibo 2008, Humbert et al. 2009, Rikxoort et al. 2014). Second, because the carbon stocks in the living biomass (coffee tree) are not included in the product carbon footprint, which only considers the carbon flow between the system and the environment (Tchibo 2008, Humbert et al. 2009). Finally, in parallel with potential strategies to mitigate and adapt to climate vulnerability in coffee producing areas, there must be an effort to increase the carbon sequestration and reduce the carbon footprint of the product.

There are few reports of this strategy in coffee, and most are described for Central America, in specific growing conditions. For example, Hergoualc'h et al. (2012) reported carbon stocks of 14.1 t/ha in a coffee monoculture under full sunshine (above and underground), against 32.4 t/ha in system of coffee shaded with Inga in Costa Rica. Moreover, Soto-Pinto et al. (2010) estimated carbon stocks below 46.3 t/ha in coffee shaded with Inga, against 39.4 t/ha in system with coffee shaded by several tree species. In addition to the coffee potential in sequestration of atmospheric carbon, these results highlight that most efforts that have been made are for areas in the countries of Central America, Africa and part of Asia, regions where the production of Arabica coffee prevails. However, there are not many studies in regions between 0° to 30° of southern latitude, despite the presumption that changes in temperature and atmosphere (CO_2) (Bunn et al. 2015) could have a strong impact on coffee production in this tropical area.

The objective of this study was to analyse the carbon balance in systems of coffee production, which can contribute to mitigating climate changes, by addressing the cultivation and production of *Coffea* spp. in the tropical regions, as the Espírito Santo state of the case study.

MATERIAL AND METHODS

Case study and time series. This study was performed considering the Espírito Santo State (area: 46 184.1 km^2), located between the meridians 39°38' and 41°50' of western longitude and the parallels 17°52' and 21°19' of southern latitude. The geographic stratification of the area planted with coffee trees (ha) was carried out based on the agriculture and cattle raising characterisation of the 2001–2012 (IBGE 2012).

Calculation of carbon stocks and footprint. The carbon stocks (t CO_2-equivalent) in the coffee production systems were calculated using the coefficient determined for coffee trees in monocultures, this coefficient is between 8.0 and 10.5 t/ha CO_2-eq (Rikxoort et al. 2014), the average coefficient of 9.25 t/ha CO_2-eq was used for standardization. The cool farm tool (CFT) greenhouse gas calculator (Hillier et al. 2011) was used to calculate the carbon footprint (t CO_2-eq), based on the coefficient determined for coffee produced (grains) in commercial unshaded monocultures (Rikxoort et al. 2014); this coefficient is between 6.2 and 9.0 t CO_2-eq/kg grains coffee, the average coefficient of 7.6 t CO_2-eq/kg grains coffee was used for standardization. The carbon balance in the coffee production systems was calculated by the difference between carbon stocks and carbon footprint, expressed in t CO_2-eq. Data of 12 consecutive years of cultivation were used to calculate carbon stocks, carbon balance and carbon footprint in the coffee production systems, because previous studies have reported this as the time of maximum carbon accumulation in coffee plants (Rodrigues et al. 2000).

Spatialization and data analysis. The areas planted with coffee trees, carbon stocks, carbon footprint and carbon balance were grouped for

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the regions (South, Central, Northeast and North) of Espírito Santo State and the data were statistically analysed for the normality verification (Kolmogorov-Smirnov, level of significance 0.05) through the Genes program (Cruz 2013). All specializations were performed with the programme ArcGIS® (version 10.2, ESRI™).

RESULTS AND DISCUSSION

The stratification of plantations of *Coffea* spp. (2001–2012) showed that, overall, the Central region has approximately 27.6% of the planted total area, followed by the Northwest region (ca. 26.7%). The South and North have somewhat smaller planted areas, with 23.8% and 21.9% of the planted area in relation to the total for the state, respectively (Figure 1).

The estimation of spatial distribution of carbon in tropical regions that produce coffee (*C. arabica* and *C. canephora*) revels higher carbon stock and carbon footprint in the years 2005 and 2010, both in the Northwest Region (Figures 2 and 3). It is also possible to observe lower values for carbon stock in the Central Region in 2011 and lower carbon footprint in the South Region during the year 2006 (Figures 2 and 3).

The carbon balance in the coffee production of tropical region was influenced by the spatial and temporal dynamics found in the estimated values of carbon stock and carbon footprint (Figures 2 and 3). The results reveals that the South region presented positive carbon balance between the years 2001 and 2011, however, the higher positive values were found in the Northwest Region between 2001 and 2005 (Figure 4). The spatialization of the carbon balance reveals that the North region presents negative values along the whole evaluated period (2001–2012), with higher negative values between 2008 and 2011 (Figure 4).

There are few studies regarding this subject in the regions between 0° and 30° of southern latitude, in general, the results indicate an increase in the negative balance after the year 2005 (South, Central and Northwest regions). This fact can be partially explained by the intense work and implementation of new technologies in these regions which occurred in the start of the 2000 decade (between 2000 and 2004), especially the recommendation of new cultivars of coffee.

This renovation scenario allows the overall crop yield of coffee to increase, associating the decrease of the plantation area and the increase in the total production of green coffee. This fact resulted in smaller carbon stock in the cultivated area and higher carbon footprint due to the larger production, causing this increase in the carbon footprint indexes (Segura et al. 2006, Dossa et al. 2008, Siles et al. 2010, Rikxoort et al. 2014). Additionally, a negative balance after 2005 may be linked to negative effects of climate change in the tropical regions, which implicates higher demand of agricultural inputs in the system to secure the production, which are directly related to the increase in carbon footprint. Another factor that must be cited is that coffee cultivation between 0° and 30° of southern latitude is predominantly done in monoculture systems, which results in decreased carbon fixation (FAO 2015).

It was observed that the southern region had the highest carbon fixation potential for coffee plants. This can be explained by the fact that this region is above 300 m of elevation above sea level, which increases the degree of suitability for the cultivation of arabica and conilon coffee; therefore, there is a rise in the potential of land use and thus higher carbon fixation by the coffee plants (Pezzopane et al. 2010, Eugenio et al. 2014).

The estimation of carbon balance indicates that along twelve consecutive years, the area cultivated with coffee trees (Arabica and Robusta) sequestrated near 2 239 476 t CO_2-eq and emitted around 10 320 223 t CO_2-eq (Table 1). Northern region presented higher potential to emit carbon, being responsible for approximately 60% of the total carbon emitted in the state. The Southern region presented positive balance, being capable of mitigate 21% of the carbon footprint, after considering the carbon fixated in the coffee trees.

The carbon footprint is reduced in 92% after quantifying the carbon stock in coffee plantations; indicating that only 8% of the carbon emissions are not compensated by the amount of CO_2 that the coffee trees can stock (Table 1). In this context, other results report that estimated emissions for the lifecycle of roasted coffee points to a carbon footprint of 8.4 kg CO_2-eq/kg, of which 55% were generated during cultivation and processing; 30% were generated during consumption; and the remaining 15% resulted from transportation, treatment and disposal of waste (Tchibo 2008,

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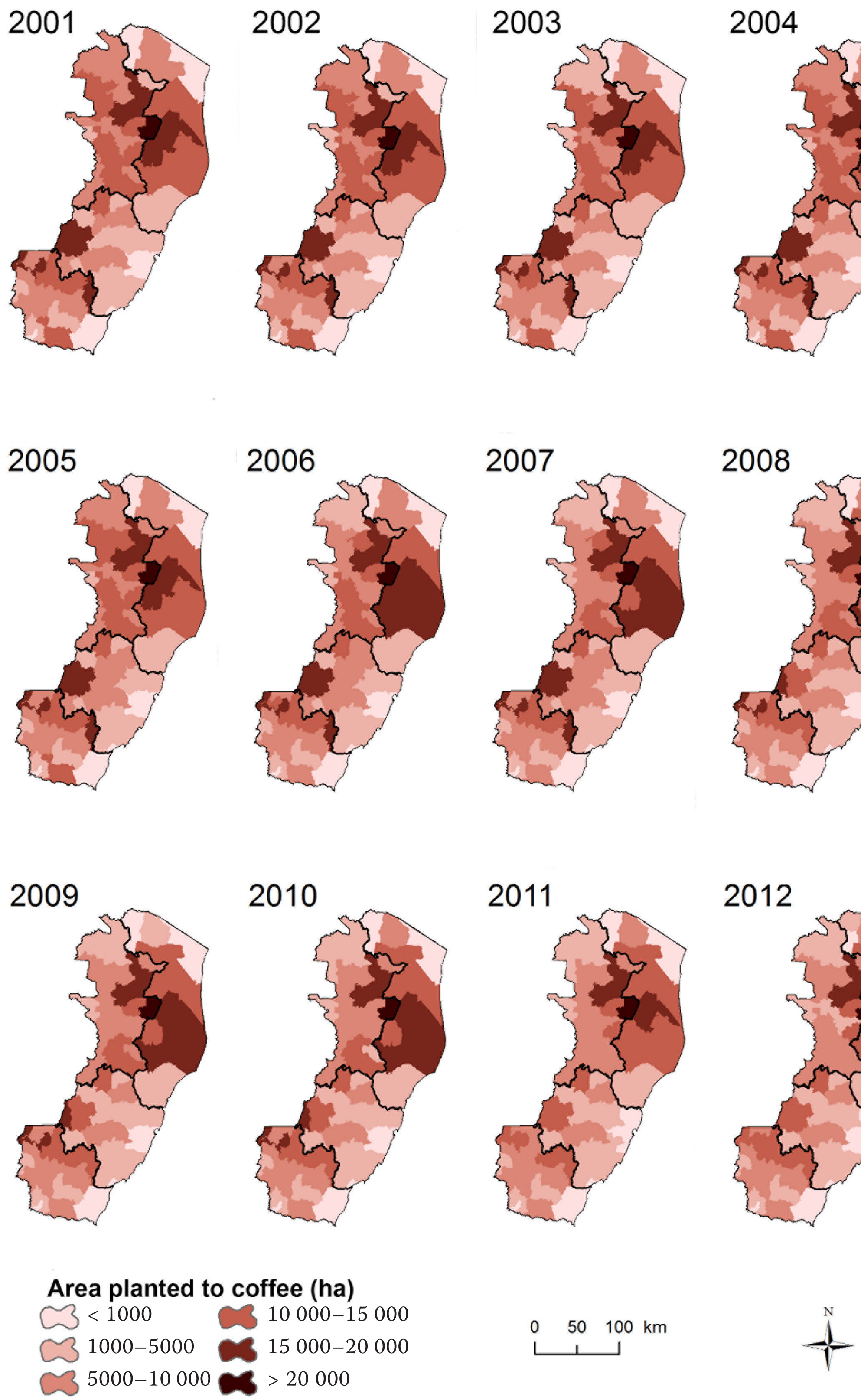

Figure 1. Stratification of the area cultivated with coffee plants (*Coffea arabica* and *C. canephora*) in 2001–2012, geographically located between the meridians 39°38'W and 41°50'W of longitude and the parallels 17°52'S and 21°19'S of latitude, universal transverse mercator projection; ellipsoid SIRGAS 2000, zone 24K

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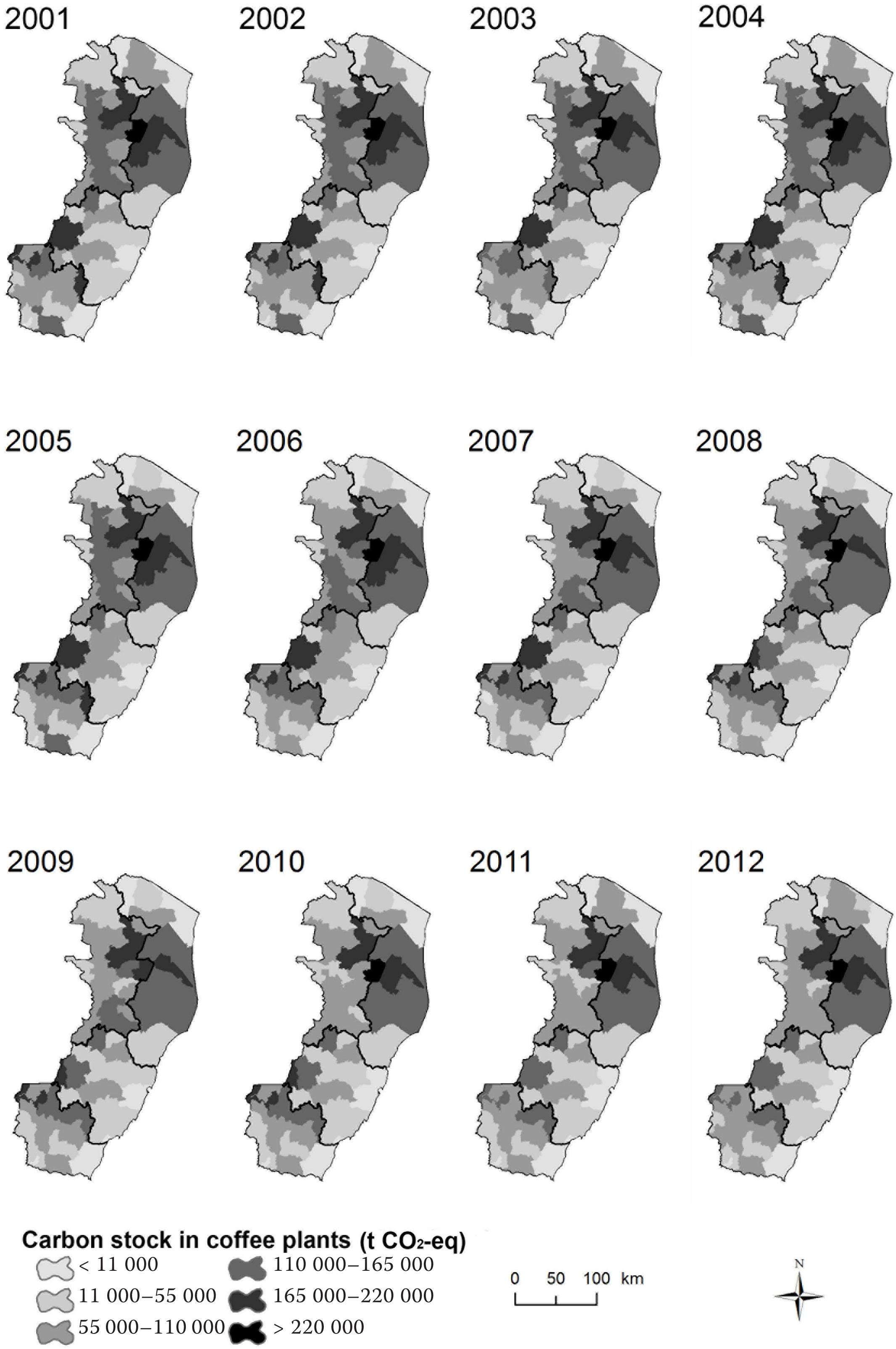

Figure 2. Spatial distribution of carbon stocks (t CO_2-eq) in monoculture of coffee plants (*Coffea arabica* and *C. canephora*) in the tropical region during 12 years of plantation (2001–2012), universal transverse mercator projection; ellipsoid SIRGAS 2000, zone 24K

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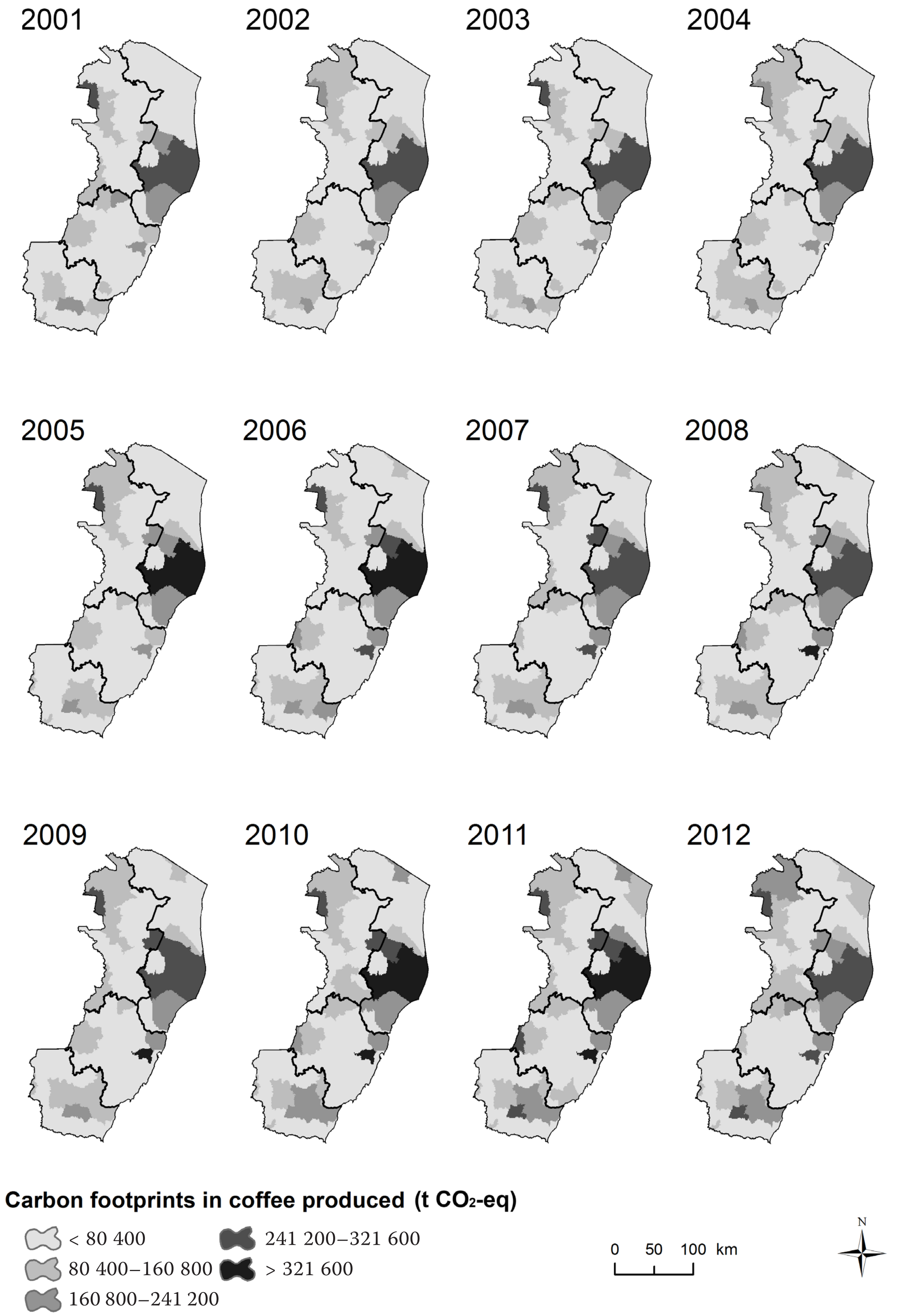

Figure 3. Spatial distribution of carbon footprints (t CO_2-eq) in monoculture of coffee plants (*Coffea arabica* and *C. canephora*) in the tropical region during 12 years of production (2001–2012), universal transverse mercator projection; ellipsoid SIRGAS 2000, zone 24K

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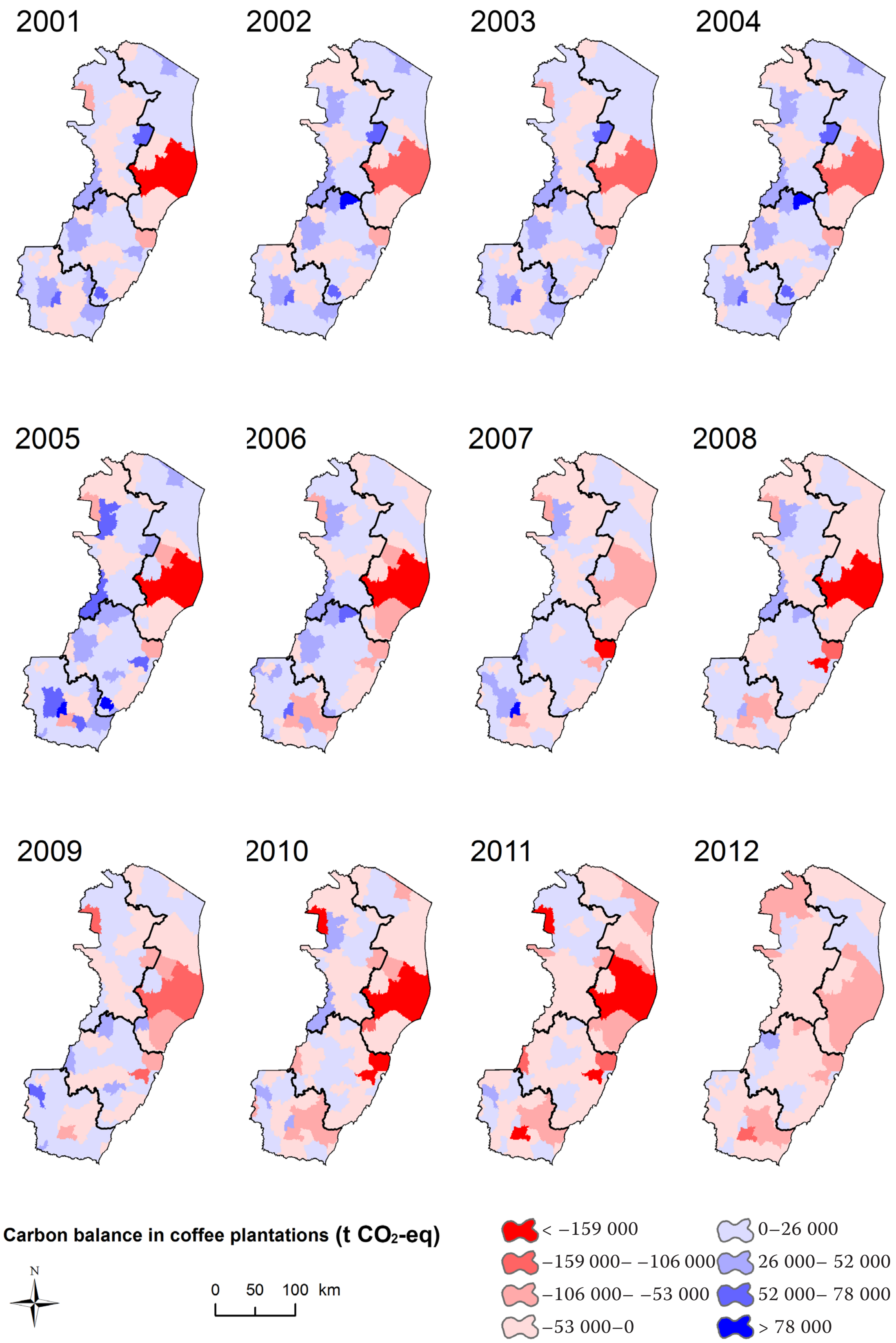

Figure 4. Spatial distribution of carbon balance (t CO_2-eq) in monoculture of coffee plants (*Coffea arabica* and *C. canephora*) in the tropical region during 12 years (2001–2012)

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Table 1. Estimated amounts of carbon (t/ha CO_2-equivalent; stock, footprint and balance) for monoculture of coffee plantation (*Coffea arabica* and *C. canephora*) in tropical regions, for 12 years of cultivation (2001–2012)

Region	Stock	Footprint	Balance
South	15 623 783.21	13 384 306.25	2 239 476.96
Central	13 371 847.67	13 541 218.38	–169 370.71
North	12 739 697.13	19 085 427.77	–6 345 730.64
Northwest	19 247 150.57	19 787 346.18	–540 195.61
Total	60 982 478.57	65 798 298.58	–4 815 820.00

Humbert et al. 2009), and these analyses exclude emissions from the coffee brew and the generation of wastewater.

The carbon balance was negative, with magnitude of 4 815 820.00 t CO_2-eq, which indicates increase in the effects of climate change and suggests that the carbon balance in coffee plantations in tropical regions is not enough to compensate the carbon footprint (Table 1). Thus, the carbon sequestration in *Coffea* spp. plantations has been described as apart of the potential mitigation strategy to climate change, mainly by the lack of methodologies to enable the full quantification of carbon in the cropping system. That is because the carbon stocks in living biomass are not included in the product carbon footprint (Tchibo 2008, Humbert et al. 2009).

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