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Environmental indicators of banana production in Brazil: *Cavendish* and *Prata* varieties

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A B S T R A C T

There are relatively few studies in the area of Life Cycle Assessment (LCA) concerning tropical perennial agricultural products, although agricultural activities in 2005 accounted for 10–12% of the total global anthropogenic emissions of greenhouse gases (GHGs) and most N_2O emissions. Furthermore, the wide diversity of these products contrasts with reduced available environmental data in Brazil. In 2012, bananas were ranked in the twelfth position on the list of commodities in Brazil and accounted for an income of US$ 1,943,869 thousand dollars. Most of the bananas produced are consumed domestically, but exports are growing. The Prata banana variety, for example, began to be exported to Europe recently. Therefore, the aim of this study is to determine environmental indicators for two varieties of banana produced in Brazil – Cavendish and Prata – in order to promote these products to consumers. This study was developed in accordance with the recommendations of the international standards ISO 14,040 and 14,044. The scope of the study was to evaluate banana production systems located at Ribeira Valley, São Paulo State and North of Minas Gerais, which is the main producer of the Prata variety. The temporal coverage was from 2011 to 2014. The functional units adopted were 1 ha of banana orchard and 1 kg banana available at retail. The global warming potential (GWP_{100}), primary energy demand (PED), abiotic depletion (AD), eutrophication potential (EP), acidification potential (AP), land use (LU), total freshwater use (TFW), blue water use (BW), terrestrial ecotoxicity potential (TETP) and human toxicity potential (HTP) of these bananas were estimated. The Prata variety showed lower GWP than Cavendish (4484.92 vs 5762.00 kg CO_2-eq ha^{-1}) due to using less nitrogen fertilizers and shorter distances, although this crop is irrigated and consequently consumes electricity. On the other hand, the Prata variety showed higher BW than Cavendish (14,800.36 vs 5300.44 m^3 ha^{-1}) due to the irrigation of this crop. Therefore, having the environmental indicators, producers can make improvements in crop management to reduce the environmental impact of the products. Moreover, indicators can be used for promoting the products to local and overseas consumers.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) (2013), CO_2 concentration increased by 40% from 1750 to 2011 – from 278 ppm to 390.5 ppm; CH_4 concentration increased by a factor of 2.5 since preindustrial times – from 722 ppb to 1803 ppb, and N_2O concentration increased by 20% – from 271 ppb to 324.2 ppb in 2011. The average rate of increase in CO_2, CH_4 and N_2O exceeded any observed rate of change over the previous 20,000 years and had a great contribution of anthropogenic activities. The contribution of agriculture to the anthropogenic CO_2 emissions is related to land use change (including deforestation, afforestation and reforestation), while anthropogenic CH_4 emissions are related to the massive increase in the number of ruminants and expansion of rice paddy agriculture. Moreover, anthropogenic N_2O emissions are mainly due to using nitrogenous fertilizers in agriculture.

Another impact category which is increasing in importance for environmental footprints of products is water use. This impact category is especially important for food products because agriculture is the sector in which most water is consumed. Water use has been assessed in Life Cycle Assessment (LCA) of fruits and vegetables such as tomatoes (Payen et al., 2015), apples, peaches

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(Vinyes et al., 2017), bananas (Roibás et al., 2015), ethanol, sugarcane, oranges, wine, etc. (Bessou et al., 2013).

Therefore, it is important to evaluate the environmental performance of the food production chain in order to identify possible hotspots and propose improvements aiming to reduce greenhouse gases (GHGs) and other emissions that contribute to various environmental impact categories, e.g. eutrophication, acidification, water use, etc. Some options to face this challenge are the following: improved cropland management, organic soil management, restoration of degraded lands, livestock management, grazing land management/pasture improvement, manure management, biomethanization and bioenergy (Smith et al., 2007).

In 2012, bananas were among the top 20 commodities in the world reaching a production of 101,992,743 tons and corresponding to an income of US$ 28,209,561 thousand dollars. In Brazil, bananas were ranked in the twelfth position in the list of commodities and accounted for an income of US$ 1,943,869 thousand dollars (FAOSTAT, 2012).

Banana production in Brazil is characterized by small producers spread over the country. The main banana producing regions are the Northeast (34.1%) and Southeast (33.5%). In 2016, banana production in Brazil accounted for R$ 8,313,352 thousand Brazilian reais (IBGE, 2016). There are only a few regions that stand out as major producers, namely: North of Santa Catarina, Ribeira Valley on the Southern coast of São Paulo state, North of Minas Gerais, Bom Jesus da Lapa in Bahia, Vale do Submédio do São Francisco, Vale do Açu in Rio Grande do Norte and Vale do Jaguaribe in Ceará (Coltro and Karaski, 2014). While states in the South and Southeast regions export to MERCOSUR countries, especially to Argentina and Uruguay, the Northeastern states, notably Rio Grande do Norte and Ceará, export to Europe (mainly the UK and Italy) (FAO, 2017).

In 2016, 6,962,134 tons of banana were produced in Brazil, which occupied a harvested area of 516,960 ha, with an average yield of 14.7 tons per hectare (IBGE, 2016). As shown in Table 1, there are large variations regarding plantation areas and production among the states, which reflects standard deviations with the same order of magnitude of the averages. The Brazilian states with the highest banana production were Bahia (16%), São Paulo (16%) and Minas Gerais (11%). The harvested area also predominated in these states, as follows: 15% in Bahia; 11% in São Paulo and 9% in Minas Gerais. However, the state that showed the highest average productivity was Rio Grande do Norte accounting for 29,790 kg ha^{-1}, while São Paulo presented the fourth highest yield, Minas Gerais the seventh and Bahia the eighth highest productivity, which indicates the influence of edaphoclimatic conditions and banana production technologies used in these regions.

Brazil exported only 80,300 tons of bananas in 2015, which were as follows: 45% to Uruguay; 30% to Argentina; 9% to the United Kingdom and 16% to others (FAO, 2017). According to Reinhard et al. (2013), domestic consumption amounts between 65% and 70% of Brazilian banana production, postharvest losses are approx. 30% and only 2%–5% is exported.

Therefore, Brazilian banana production is almost entirely targeted at the domestic market due to its large population and high per capita consumption; 29.1 kg bananas per inhabitant per year (FAO, 2009). According to Lichtemberg et al. (2007), Brazil has not developed good postharvest handling and conservation practices for transportation to overseas markets as more traditional banana exporting countries have, such as Ecuador, Costa Rica, the Philippines, Guatemala, Colombia, etc. Another reason for the low level of banana postharvest care in Brazil is because the largest part of domestic production comprises bananas from the Prata subgroup, which is preferred by most Brazilian consumers and it is more resistant to postharvest injuries and diseases, but with less access to export markets. Therefore, except for the states of São Paulo, Paraná and Santa Catarina, where Cavendish banana crops prevail, most of the Brazilian banana production is from the Prata variety (Lichtemberg et al., 2007).

Decision-makers and producers have been forced to search for scientific information regarding environmental performance of food products through LCA studies due to the increase in consumer's ecological awareness. However, more research should be carried out, as well as developing methodologies to continue improving LCA studies on tropical perennial agricultural products, whose wide diversity contrasts with the reduced data available (Bessou et al., 2013; Cerutti et al., 2014; Coltro et al., 2009; Recanati et al., 2018) because these data do not exist, or they have not been published.

Studies on the carbon footprint of Cavendish banana production have been developed in some countries, such as Costa Rica (Luske, 2010; Svanes and Aronsson, 2013) and Ecuador (Iriarte et al., 2014; Lescot, 2012; Roibás et al., 2016; FAO, 2016). Various studies have reinforced the belief that the life cycle stage with the most significant impact on the banana production chain is transportation, mainly due to overseas transportation, followed by agricultural production. The transportation stage of the carbon footprint of bananas produced in Central and South America and sold to the USA showed the largest contribution of emissions (36%) by this supply chain according to a study developed by Craig et al. (2012). Moreover, the same applied for bananas produced in South America and sold to Europe, which accounted for 31% according to a study developed by Roibás et al. (2015) and from 27% to 67%, depending on the scenarios considered by the study developed by Iriarte et al. (2014).

These studies showed the farm stage as the second largest contributor to the carbon footprint, which corresponded to 22% of the Cavendish banana production carbon footprint in studies developed by Craig et al. (2012) and Roibás et al. (2015) and ranged from 23% to 53% in the study developed by Iriarte et al. (2014), depending on the scenarios considered.

Therefore, the aim of this study is to assess environmental indicators of banana production in Brazil through LCA, namely global warming potential (GWP_{100}), primary energy demand (PED), abiotic depletion (AD), eutrophication potential (EP), acidification potential (AP), terrestrial ecotoxicity potential (TETP), human toxicity potential (HTP), land use (LU), total freshwater use (TFW)

Table 1
Main regions of banana production in Brazil in 2016 (IBGE, 2016).

Region	Cultivated area (ha)	Harvested area (ha)	Production (t)	Average yield (kg ha^{-1})
Bahia State	76,000	70,000	1,125,000	16,071
São Paulo State	56,396	52,896	1,124,560	21,260
Minas Gerais State	48,962	44,728	772,845	17,279
Brazil	516,960	474,054	6,962,134	14,686
Average ± SD	19,147 ± 20,448	17,558 ± 18,463	257,857 ± 320,211	14,112 ± 5601
Variation Interval[a]	192–76,000	190–70,000	3652–1,125,000	6949–29,790

[a] Intraregional variability.

and blue water use (BW), considering the main production regions in Brazil. These environmental indicators can facilitate the access of this product to the export market. The LCA was applied from a farm-to-retail perspective in order to quantify the environmental performance of two banana varieties available at retail stores in the domestic market: Cavendish and Prata bananas.

2. Methods

The LCA study was conducted in accordance with the recommendations of the International Standards, ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006).

2.1. *Goal and scope definition*

The goal of this study was to develop the LCA (cradle-to-gate) of two varieties of banana produced in Brazil: Cavendish, a subgroup of the AAA genomic group; and Prata, a subgroup of the AAB genomic group in order to estimate the potential environmental impacts of this tillage and to realize how to increase the environmental sustainability of these products. Both banana varieties are of great economic importance in Brazil, as bananas generated the 10th highest income in 2015 equivalent to US$ 1750 million (IBGE, 2016). The environmental indicators obtained in this study could help develop the Environmental Product Declaration of these products and increase the commercialized volumes of these products due to the rise in the number of consumers who are more aware of the environmental impacts of their purchasing choices.

The scope of the study was to evaluate the banana production systems located at Ribeira Valley in Sao Paulo State (Cavendish and Prata varieties) and North of Minas Gerais (Prata variety). Ribeira Valley corresponds to 36,000 ha out of 56,000 ha of Cavendish banana cultivation in Sao Paulo State, while the North of Minas Gerais has a production of more than 5400 tons of Prata bananas per week, which is the main producer of Prata variety. Geographic coordinates of these regions are 43 to 48° W longitude and 15 to 24° S latitude. The climate is subtropical, warm temperate, with well distributed rainfall and well-defined seasons. The average annual precipitation is 1500 mm and the average relative humidity is approximately 75%. Its average annual temperature is 19.1 °C.

2.2. *Temporal and spatial coverage*

The temporal scope of this study comprised the reference crops of 2011/12, 2012/13 and 2013/14. The data refer to a productive area of approximately 300 ha of Cavendish banana cultivation, the data of which were provided by 4 producers and approximately 60 ha of the Prata banana cultivation, with data provided by three producers.

This study concentrated on regions that stand out as being among the largest producers, namely Ribeira Valley (in São Paulo State) and Northern Minas Gerais whose characteristics are described below.

2.2.1. *Ribeira Valley*

The producers of this region generally have only banana plantations on the property. Despite the high volume of bananas produced in this region, its prominence in the fruit market is due to the proximity of this producing region to the main consumer market in Brazil: Greater São Paulo, the largest metropolitan region in Brazil, which has about 21.2 million inhabitants and one of the ten most populous metropolitan regions in the world.

The region has an ideal climate for banana cultivation as there is plenty of heat and high humidity. The drawback to the cultivation in the region is the strong winds at some times of the year, which blow over the banana trees, forcing producers from São Paulo to cut the bunches before the ideal time, affecting the supply momentarily and in the following months (Matthiesen; Boteon, 2003).

Most of the bananas produced in the Ribeira Valley are for the wholesale market, concentrated at the Company of Warehouses and General Warehouses of São Paulo - CEAGESP, which sold 78,679 tons of bananas in 2013 (70% Cavendish and 21% Prata among other banana varieties).

2.2.2. *Northern Minas Gerais*

Northern Minas Gerais is a strong region producing Prata bananas. The dry climate of this region, similar to the climate of the Northeast region, benefits the development of the crop and reduces expenses spent on disease controllers, but this region is also hampered by the strong summer winds that cause banana trees to fall down.

Electric energy, fundamental to the operation of the irrigation system used in this cultivation region, increases production costs, and consequently the final price of regional bananas.

The local production is large and of excellent quality, but the taste of the main Prata variety grown in the region is still not very known on the international market, as it is dominated by Cavendish.

A drawback for banana production in the northern region of Minas Gerais is the distance from this region to the São Paulo market, which reduces the competitiveness of bananas from the north of Minas Gerais in this market. Bananas produced in regions nearer, such as Ribeira Valley, transported with smaller freights, ensure most of the São Paulo market. Wholesale is the main way of selling bananas to producers in this region, and they serve the State Supply Centers - CEASA from Belo Horizonte, Rio de Janeiro and São Paulo (Matthiesen; Boteon, 2003).

A summary of the characteristics of these banana-producing regions is shown in Table 2.

2.3. *Functional unit*

According to Cerutti et al. (2014), the combination of mass-based and land-based functional units can give a more complete picture of the environmental impacts of orchard systems. Furthermore, the quantity of edible content of the mass-based functional unit should be indicated to scale environmental impacts related to the quantity effectively consumed. Therefore, the following functional units were adopted in this study:

- 1 ha of orchard – related to the management of the production area; and
- 1 kg of bananas available at retail in the domestic market – related to losses along the productive chain. The edible content of bananas is 70% on average.

2.4. *System boundaries*

System boundaries comprised farming, including transportation after harvest, fertilizer and corrective production, electricity generation, fuel production, packaging production, ripening, transportation to the retailer and landfill degradation of banana loss in retail (Fig. 1). All the stages included in the system boundary were taken into account to estimate the environmental performance of both banana varieties.

2.5. *Inventory analysis*

Farm-specific data along with ripening, transportation and retail

Table 2
Characteristics of the banana-producing regions in Brazil evaluated in this study (adapted from EMBRAPA, 2009).

Production region	Ribeira Valley	Northern Minas Gerais
Characteristics of producers	Small and medium producers with average area of properties ranging from 10 to 20 ha	Small and medium producers, whose properties have areas ranging from 5 to 20 ha
Infrastructure condition	Part of the properties do not have good postharvest infrastructure and classification of the fruit produced, which impairs the quality of the product and its durability on the shelf. On the other hand, there are also properties with good technification in both the production and processing stages.	Good technification
Cultivated varieties	Cavendish has an average yield of 25 tons ha^{-1} and Prata has an average yield of 13 t ha^{-1}	Cavendish yields 60 t ha^{-1} when grown under irrigation. Under the same conditions, the Prata variety reaches 35 t ha^{-1}
Target market	Greater São Paulo	Belo Horizonte, Rio de Janeiro, Brasília and Goiânia
Advantages	Proximity with Greater São Paulo	Dry climate benefits the development of banana culture in the region and reduces expenses incurred by disease controllers
Disadvantages	Climate records high temperature and high humidity, a situation that favors the proliferation of fungi. It incurs higher costs in disease control than in the drier regions.	Distance between the production area and the São Paulo market

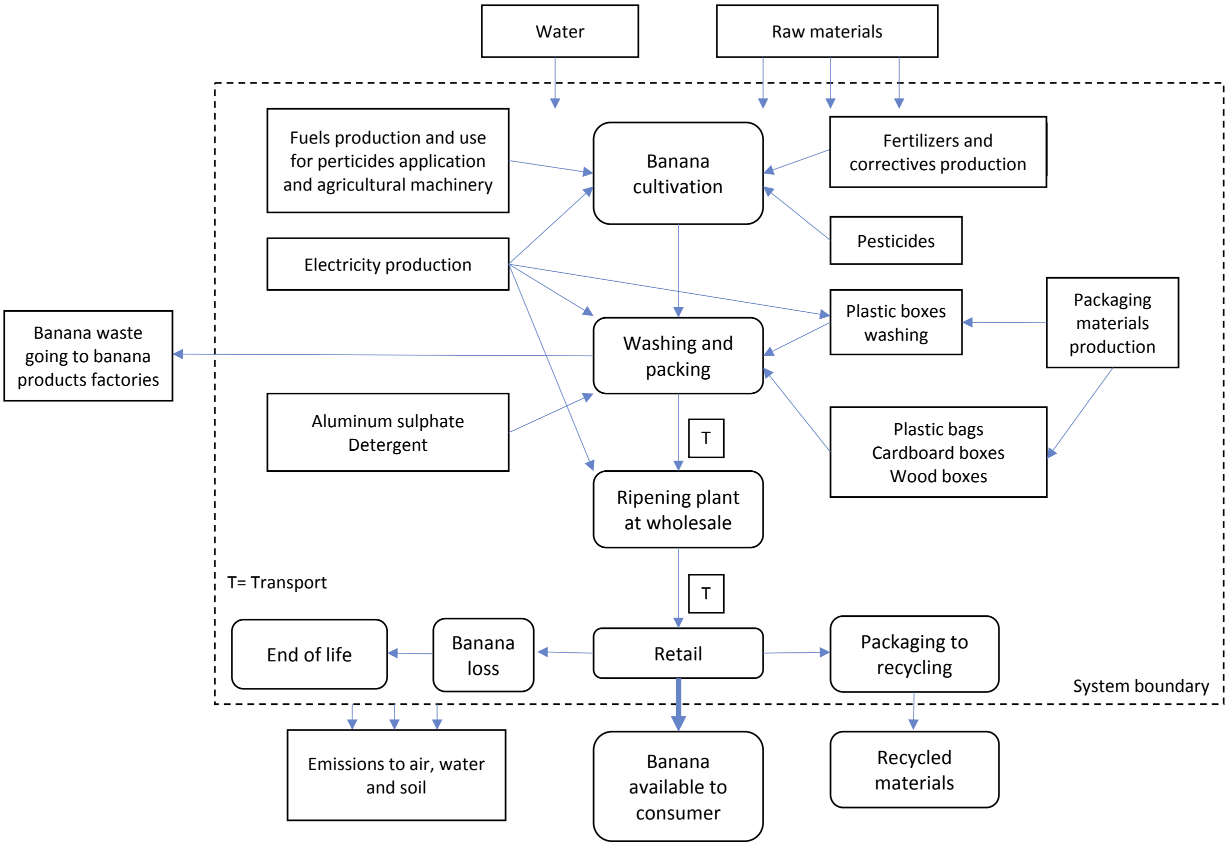

Fig. 1. System boundary adopted in this study.

companies' data were combined in order to model the banana production systems, which covers 3 years of real production and distribution of bananas. Primary data were obtained from interviews conducted with personnel involved throughout the banana production chain, i.e. farm owner and employees, banana producer associations, wholesalers, retailers, etc.

Electricity generation and transportation models specifically developed for Brazil, taking into account the electricity power grid mix for 2012 and the GHG emission factors from GHG Protocol Brazil, were adopted (Coltro et al., 2003; GHG, 2012). Specifically, the electricity power grid mix comprised 91.18% hydroelectric, 3.17% nuclear, 2.65% natural gas, 1.15% coal, 0.42% fuel oil, 0.24% diesel, 0.39% eolic and 0.80% biomass.

Secondary data obtained from recognized databases available in the GaBi 6 Product Sustainability software were used for fertilizers and correctives (PE International A.G.), ethanol (Ecoinvent v3.1) and packaging production (ELCD database 2.0).

The inventory quantities of energy consumption and renewable/non-renewable resources, cultivated areas, yields and water usage for irrigation and washing (water abstracted from surface water) were analysed.

This study does not include environmental impacts related to capital goods, i.e. natural resource and energy consumption for constructing agricultural machinery, irrigation systems, trucks and other items.

2.5.1. Cultivation

The agricultural stage comprises fertilization, pest management, irrigation (when applicable) and harvesting. The nursery stage was not considered in this study, but rather the plants in the production stage. The following inputs were taken into account: energy use (fuel production and usage and electricity production and usage by irrigation pumps); water use; production and application of fertilizers and correctives, and pesticide application (fungicides, insecticides and herbicides) and packaging production.

Small to medium banana properties were evaluated. Usually banana yields increase when plant density rises. At the same time, the weight of the bunch reduces due to competition between the plants. As can be seen in Table 3, despite Cavendish plantations adopting higher plant density than Prata crops, the yield of the latter is greater. This is due to the size of the banana bunches, which are heavier in the case of the Prata variety – in irrigated banana plantations from northern Minas Gerais, the bunch reaches over 50 kg while in the case of Cavendish, the bunch weighs from 10 to 60 kg. Due to its higher height and leaf area, the Prata banana requires larger row spacing, such as 2 × 3 m, 2 × 3.5 m, 2 × 4 m, 3 × 3 m, 3 × 3.5 m, 2.5 × 4 m, 3 × 4 m and 4 × 4 m, depending on local conditions and market requirements (Lichtemberg et al., 2007).

It was assumed during the timeframe evaluated in this study that the plantations are in a steady state situation and the land use change was considered null since the studied plantations were more than 20 years old (IPCC, 2006a).

Land use was calculated taking into account the plantation area during the occupation time of 10 years of banana production and the respective number of productive cycles per variety, as follows: 8 cycles of 15 months long for Cavendish and 8.6 cycles of 14 months long for the Prata subgroup.

Biomass production during the banana cultivation stage reached the amount of up to 200 t/ha/year due to pruning the banana trees after harvesting the fruit, which are usually cut and used to cover the soil to maintain its quality (Lichtemberg et al., 2007). However, carbon or mineral element sequestration not considered in this study.

Due to the humidity conditions in the regions evaluated in this study, banana plants are mainly attacked by Sigatoka (disease caused by a fungus) that causes serious damage to the leaves, a sharp drop in production and early maturation of fruits. Aerial applications of fungicides are used to control the damage caused by the fungus. On average, ten applications of fungicides per year are carried out by light aircraft. Ethanol is used as aviation fuel for aerial fumigation of the banana plantations. Production and fuel consumption (ethanol) were included in the boundary for aerial pesticide sprayings.

2.5.2. *Production and application of fertilizers*

The environmental aspects related to the production of NPK fertilizers, i.e. urea (technology mix, nitrogen content 46%), triple superphosphate (technology mix, phosphorus compound contents 45% as P_2O_5) and potassium chloride (technology mix, potassium compound contents 60%) were taken from a recognized database available in the GaBi 6 Product Sustainability software program and included in the boundary. Nitrogen and phosphate emissions from producing and applying fertilizers were included within the system boundary according to the following descriptions.

Direct carbon dioxide (CO_2) and nitrous oxide (N_2O) field emissions due to applying fertilizers were estimated following the tier 1 approach stated by the IPCC guidelines (IPCC, 2006a). CO_2 emission was estimated as 20% volatilization of N-based fertilizer. Nitrous oxide (N_2O) emissions into the air were estimated as 1.33% of N-based fertilizer where:

- 1% is due to direct N_2O emissions of N inputs from mineral fertilizers as a result of loss of soil carbon;
- 0.33% is due to indirect N_2O emissions associated with:
    - volatilized and re-deposited N, which accounts for 0.10% (1% of the fraction of synthetic N fertilizer applied that volatilizes as NH_3 and NO_x, which is 0.1), and
    - N lost through leaching/runoff, which results in 0.23% (0.75% of the fraction of N added to soil which is lost through leaching and runoff as NO_3, which is 0.3).

Nitrogen emissions were estimated according to Brentrup et al. (2000), as follows: ammonia (NH_3) emissions were assumed to be 8% and, consequently, emissions of nitrogen oxides (NO_x) were assumed to be 2%. Nitrate leached to water was estimated as 30% of N-based fertilizer, while phosphate was assumed to be 1% of the P-based fertilizer (Erickson et al., 2001; Smil, 2000).

2.5.3. *Production and application of correctives*

The environmental aspects related to the production of the corrective gypsum stone (CaSO4 dihydrate) and limestone (CaCO3, washed) were taken from a recognized database available in the GaBi 6 Product Sustainability software program and included in the boundary. CO_2 emission was estimated as 12% of calcitic and 13% of dolomitic limestone applied to correct the acidity of the soil following the tier 1 approach stated by IPCC guidelines (IPCC, 2006a).

2.5.4. *Packaging*

During the banana cultivation, the fruit was covered with plastic bags so as to protect it from insects during growth. After harvesting the bunches of bananas, these plastic bags were used to make a cushioned base which was a support for transporting the bananas by tractors to the packing house inside the property. After using them at least ten times, the plastic bags were then recycled. Therefore, the weight of one plastic bag - considered as 0.025 kg (Svanes; Aronsson, 2013) was multiplied by the number of plastic bags used per crop and this amount of plastic waste was considered as open loop recycling, i.e. recycling of used plastic bags in a different product system (Guinée et al., 2002).

After washing and selecting the fruit according to quality

Table 3
Field characteristics of both banana varieties evaluated in this study.

Crop	Cavendish[a]			Prata[b]		
	2011/12	2012/13	2013/14	2011/12	2012/13	2013/14
Plantation area (ha)	10–135	12–135	12–135	10–50	10–25	10–25
Yield (t ha^{-1})	21–27	23–27	25–27	15–30	13–32	11–35
Density (plants ha^{-1})	1600–2500			900–1270		
Plant height (m)	1.2–2.4 m			2.2–4.5 m		
Bunch weight (kg)	10–60 kg			>50 kg		

[a] Data refer to 4 producers.
[b] Data refer to 3 producers.

standards, the bananas were packed in boxes which were plastic crates with 20-kg net weight capacity, wooden crates with 22.5-kg net weight capacity or corrugated board boxes with 15-kg net weight capacity, with a plastic liner. In this study 63% plastic crates, 22% wooden crates and 15% corrugated board boxes were considered, on average. In the case of plastic crates, a replacement of 10% per year was considered due to loss because of theft. Since plastic crates are reusable, the boxes were reused 10 times before being recycled and this was also taken into account. The plastic crates were washed in a diluted solution of chlorinated alkaline descaler prior to reuse, and the water and energy consumption were considered. Plastic liners were not considered in this study.

The environmental aspects related to the production of these packaging materials were taken from a recognized database available in the GaBi 6 Product Sustainability software program and included in the boundary.

2.5.5. Packing house

Afterwards, manually harvested bunches of bananas were transported from the field to the packing house via steel cables powered by employees or by tractors, depending on the slope of the field. The quality of the bananas was evaluated at the packing house and each bunch was cut to have six to ten pieces of fruit. The bananas were then washed in water containing a small amount of aluminum sulfate (winter) and detergent (summer). The water was reused for 15 days before discarding it.

2.5.6. Transportation

The bananas were distributed by trucks running on conventional diesel oil, which emitted 10 mg of sulfur per liter and had a fuel consumption of 0.30–0.37 L diesel km^{-1}, depending on the truck load capacity (15–29 tons). A load factor of 85% was adopted for all the transportation steps due to the volume occupied by the load.

In the case of refrigerated trucks (29 ton trucks travelling long distances, e.g. 3000 km from Northeast to São Paulo which takes 37 h on average), a fuel consumption of 0.45 L diesel km^{-1} was estimated, which corresponds to a 20% increase in diesel consumption (Tassou, 2009). Furthermore, 1.5 g refrigerant gas R404A per truckload per hour was used. The refrigerant gas R404A is a mixture of CFCs and HCFCs - chlorofluorocarbons and hydrochlorofluorocarbons, as follows: 44% HFC-125, 52% HFC-143a and 4% HFC-134a. A 10% leakage of the refrigerant gas was assumed (Luske, 2010).

With the exception of refrigerated trucks, which carry refrigerated food on the return trip to the Northeast region, all other trucks returned empty and their transport distances were doubled.

2.5.7. Ripening

Green bananas are transported from the farm to the storage warehouses where they are ripened in specially built chambers by exposure to ethylene gas with controlled temperature and relative humidity. The amount of ethylene used in the chambers and the exposure time depend on the banana variety, i.e., on average, 1.74 E^{-4} kg of ethylene kg^{-1} bananas and 62.4 h of exposure were used for the Cavendish bananas and 1.77 E^{-4} kg of ethylene kg^{-1} bananas and 37.3 h of exposure for the Prata bananas. Over ripening is usually avoided in order to minimize waste prior transportation to retail. Besides ethylene, energy consumption was also accounted for in this stage: 0.151 kWh kg^{-1} bananas for Cavendish and 0.098 kWh kg^{-1} bananas for Prata.

2.5.8. Distribution and retail

In the Brazilian banana market, wholesalers are still the main distributors of the product to the retail market. They buy and sell bananas in boxes and often perform other functions such as product classification and standardization, ripening, producer financing, storage, transportation, etc. There are several types of wholesalers depending on the area of operation and the marketing functions. Among them are national wholesalers and private distribution centers. In Brazil, bananas are usually sold by national wholesalers such as CEASAS and CEAGESP and their main clients are fruit and vegetable stores, town markets and mini neighborhood supermarkets (Matthiesen and Boteon, 2003).

Therefore, after ripening, the bananas are transported from the wholesalers' warehouses to the retail stores, considering an average distance of 24 km in trucks loaded with 7 tons, which return empty. Fuel consumption was 5.4 km L^{-1}. The bananas are kept at room temperature at retail, where they are sold unpacked. Usually consumers pack bananas in low density polyethylene (LDPE) plastic bags, but these bags were not considered in this study because the consumer stage was outside the system boundary.

Methane (CH_4) emission from landfilled banana losses (10% - Cavendish and 7% - Prata) due to maturation at retail market was estimated following the tier 1 approach stated by IPCC guidelines taking into account food waste in tropical zones with the following parameters: degradable organic carbon – DOC of 0.15; fraction of DOC that can decompose in anaerobic conditions of 0.5; methane correction factor of 0.6 and fraction of methane, by volume, in generated landfill gas of 0.5 (IPCC, 2006b).

2.6. Allocation

Despite the fact that some of the farmers send banana losses from the farm to industry to produce various banana products, e.g. salty banana chips, banana candy, etc., 99% of bananas commercialized in Brazil are *in natura*. Therefore, no allocation was adopted in this study, i.e. 100% of the burdens were attributed to bananas at the farm gate.

2.7. Impact assessment

The environmental impact categories adopted in this study are those considered most relevant for the Brazilian situation. Climate change (global warming potential for a 100-year perspective - GWP_{100}, excluding biogenic carbon), abiotic depletion (ADP fossil), eutrophication potential (EU), acidification potential (AP), terrestrial ecotoxicity potential (TETP) and human toxicity potential (HTP) were estimated according to the CML 2001–April 2013 method (Guinée, 2002) as this method is globally oriented and more appropriate for the Brazilian context. The primary energy demand (PED) from renewable and non-renewable resources (net calorific value) was calculated using the GaBi 6 Product Sustainability software program, which takes into account direct and indirect fuel consumption (machinery and fertilizers). Land use (LU), total freshwater use (TFW), blue water use (BW), and banana loss were also considered (Guinée, 2002; Hoekstra et al., 2011). Data storage and modeling were performed using the GaBi 6 Product Sustainability software program (PE, 1992–2015).

3. Results and discussion

Results obtained from this study for bananas at the farm gate and bananas in retail shops are shown separately according to the banana variety evaluated, i.e. Cavendish and Prata varieties. A comparison of the results obtained from this study with LCA results for banana and tropical fruits available in the literature is also shown.

3.1. *Cavendish bananas at the farm gate*

Table 4 shows the main life cycle inventory inputs over the three-year Cavendish banana cultivation stage evaluated in this study taking into account 1 ha of banana orchard. The main variation among the crops are the total energy use, which is a consequence of the reduction in using some resources such as fertilizers, gypsum and fuel. Electricity was used only in the 2013/14 crop due to the irrigation adopted by some farms during this crop as a result of the dry weather which occurred this year in the studied area (Ribeira Valley region).

Irrigation is not usual for banana production in Brazil. However, water use increased during the 2013/14 crop due to the dry weather observed, while in the previous crops water was used only for washing bananas at the packing house. Throughout the years, an increase in the yield was observed.

According to the farmers, on average, 1.2 kg fertilizers plant^{-1} was applied every year, mainly urea, triple superphosphate and potassium chloride with different proportions of NPK. The use of nitrogen fertilizers in this study was 306 kg N ha^{-1} or 12 kg N t^{-1} bananas (active element), which is higher than the amount used in the study developed by Iriarte et al. (2014), which was 265 kg N ha^{-1}.

3.1.1. *Environmental indicators of Cavendish bananas at the farm gate*

Table 5 shows the life cycle impact assessment over the three-year Cavendish banana cultivation stage evaluated in this study taking into account 1 ha of banana orchard. Data from several crops are more representative of the evaluated product as the effect of eventual seasonality on the final result is reduced.

The average GWP obtained for the crops studied was 5762.00 kg CO_2-eq ha^{-1} or 225.86 kg CO_2-eq t^{-1} produced bananas. The use of cover crops (Impatiens, etc.) was observed in some of the farms evaluated, which helps reduce chemical fertilizers and, consequently, the GWP of banana production. This was observed throughout the years evaluated, i.e. the use of N fertilizer decreased from 674.56 kg ha^{-1} or 26.68 kg t^{-1} to 660.78 kg ha^{-1} or 20.78 kg t^{-1} and GWP_{100} also decreased from 5840.17 kg CO_2-eq ha^{-1} or 232.58 kg CO_2-eq t^{-1} to 5741.53 kg CO_2-eq ha^{-1} or 220.53 kg CO_2-eq t^{-1}. The results obtained are in agreement with the results obtained by Svanes and Aronsson (2013), who obtained the GWP value of 220 kg CO_2-eq t^{-1} bananas for Cavendish banana produced in Costa Rica. The GWP values obtained by Iriarte et al. (2014) in a study carried out in Ecuador for the harvests from 2009 to 2011 (from 210 to 260 kg CO_2-eq t^{-1} bananas) are also in agreement with the results obtained from the present study.

As can be seen in Fig. 2, GHG emissions are mainly due to field emissions (54%), followed by fertilizer production (28%) and packaging production (12%). The GHG emissions in the field are mainly due to the direct and indirect emissions of N_2O (0.067 kg CO_2-eq or 29%) due to the use of nitrogen fertilizer (urea) followed by CO_2 emissions (24%) also due to urea application (0.017 kg CO_2-eq), as well as limestone (0.037 kg CO_2-eq) used for soil remediation. Besides, urea is responsible for 64% of emissions associated with fertilizer production.

The results of this study are in accordance with Iriarte et al. (2014) who also observed that field emissions due to nitrogen fertilizer application are the main contributors to GHG emissions (49% or 0.11 kg CO_2-eq), followed by fertilizer production, 22%. Our results are also in accordance with a study carried out by Svanes and Aronsson (2013), which are 29% due to N_2O direct emissions, 23% due to fertilizer production and 7% due to fossil fuel combustion. A study developed by Luske (2010) also identified N_2O direct emissions as the main contributor to GHG emissions at the farm stage (47%) followed by fertilizer production (36%), fungicides production Roib (9%) and fuel burning (7%).

Bananas need large amounts of fertilizers but using cover crops and banana trees as a source of nutrients when left on the soil after harvesting may reduce the need for the use of synthetic fertilizers (Lichtemberg et al., 2007). This is the practice adopted by the farmers in this study, i.e. organic waste is left on the ground at the banana plantations, which contributes to soil fertilization and reduces the need for synthetic fertilizers. In this situation, CH_4 is not

Table 4
Life cycle inventory for **Cavendish bananas at the farm gate** for the reference crops 2011/12, 2012/13 and 2013/14 (FU = 1 ha).[a]

Parameter	Unit	2011/12	2012/13	2013/14
Energy				
Total	MJ	71,472.61	69,656.22	71,383.80
Electric (public grid)	MJ	–	–	423.87
Diesel	kg	88.12	93.88	93.83
Ethanol	kg	45.78	45.68	45.29
Non-renewable energy resources	kg	1423.76	1396.46	1402.52
Oil	kg	510.88	504.98	506.62
Natural gas	kg	654.77	641.19	643.36
Other resources				
Water for washing bananas	kg	6304.34	5749.38	5729.57
Water for irrigation Fertilizers[b]	kg	–	–	784,939.27
N fertilizer (mainly urea 46% N)	kg	674.56	661.91	660.78
Phosphate fertilizer (45% P_2O_5)	kg	448.26	438.12	430.48
Potassium fertilizer (KCl 60% K_2O)	kg	1346.64	1316.25	1321.05
Micronutrients (Zn, Mn, Fe, Cu, B etc.)	kg	95.14	95.96	96.94
Correctives[b]				
Gypsum (natural gypsum)	kg	971.44	886.05	883.06
Limestone (calcium carbonate)	kg	1832.60	1808.48	1903.90
Pesticides[b]				
Fungicides (sulfur based)	kg	18.92	20.04	19.95
Insecticides (imidacloprid)	kg	4.87	5.42	5.36
Herbicides (glyphosate)	kg	–	–	0.82
Mineral oil (for pulverization)	kg	75.08	76.64	75.81
Yield	kg	25,110	25,412	26,035

FU = functional unit.

[a] Weighted average for four farms.

[b] Active and filler elements.

Table 5
LCIA results for **Cavendish bananas at the farm gate** for the reference crops 2011/12, 2012/13 and 2013/14 (FU = 1 ha).

Environmental indicator	Unit	2011/12	2012/13	2013/14	Average
GWP_{100}	kg CO_2-eq	5840.17	5704.27	5741.53	5762.00
Acidification	kg SO_2-eq	69.55	68.10	68.73	68.80
Eutrophication	kg PO_4^{3-}-eq	60.77	59.46	59.62	59.95
Total freshwater use	m^3	19,682.47	19,595.06	19,661.21	19,646.29
Blue water use	m^3	4540.39	4507.86	6853.03	5300.44
PED	MJ	71,480.39	69,664.63	71,391.95	70,845.80
ADP fossil	MJ	55,011.24	54,049.37	54,261.10	54,440.68
TETP	kg DCB-eq	17.46	17.45	17.86	17.59
HTP	kg DCB-eq	1525.60	1562.31	1574.31	1554.08
Land use	m^2yr	13,293.00	13,059.77	13,176.36	13,176.40

GWP = global warming potential; PED = primary energy demand; ADP = abiotic depletion; TETP = terrestrial ecotoxicity potential; HTP = human toxicity potential.

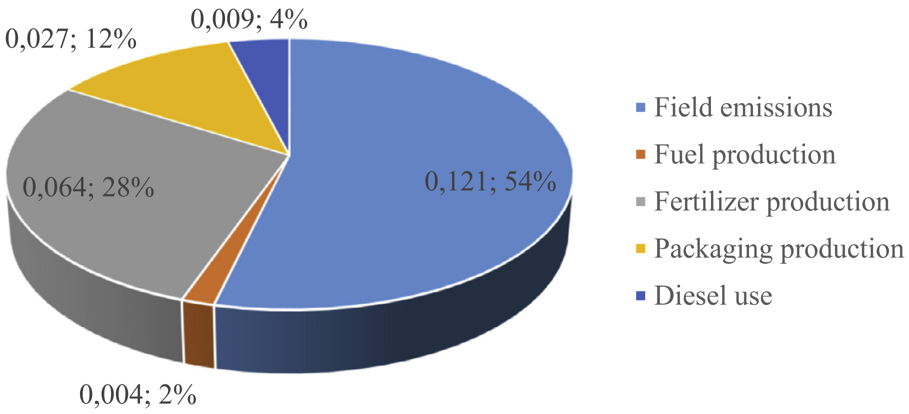

Fig. 2. GHG emissions for Cavendish banana production at farm level, average value for crops 2011/12, 2012/13 and 2013/14.

generated as there are no anaerobic conditions. Moreover, CO_2 emission during aerobic degradation was also not accounted for due to the biogenic origin of waste. This agrees with the study developed in Ecuador by Roibás et al. (2016), where farmers adopted the same procedure. On the other hand, a study developed in Costa Rica by Svanes and Aronsson (2013) identified CH_4 emissions from landfilling organic waste as one of the main contributors at the farm stage (34% or 0.075 kg CO_2-eq kg^{-1} banana). This gives us an idea of the contribution of this cultivation practice to reduce GHG emissions at the farm stage.

Films used to cover the banana bunches contributed 2% to the GHG emissions, while the largest contribution of packaging (10%) was due to the boxes used to pack the bananas for transportation.

Burning diesel by agricultural machinery showed a contribution of 4% to the CO_2 emissions, while burning ethanol by airplanes for plant spraying accounted for only 0.02% due to its renewable source.

No large variation among the values obtained for land use, eutrophication and acidification categories was observed for the harvests evaluated (Fig. 3). For the impact categories of ADP fossil, PED and GWP, there was a tendency to reduce the value in the most recent harvest evaluated. However, an increase was observed in the last harvest evaluated in the case of blue water use and HTP.

The increase in blue water use in the last evaluated harvest is due to irrigation, which is not common in banana productions in Brazil. However, there was a severe drought in the banana-producing region evaluated in this study in 2013/2014 and the farms which have irrigation systems made use of it, increasing blue water use.

Blue water use found in this study (5300.44 m^3 ha^{-1} or 207 m^3 t^{-1} banana) is higher than the value obtained by Roibás et al. (2015) for banana cultivation in Ecuador (171 m^3 t^{-1} banana). This difference is probably related to the lower harvest yield per hectare of banana plantations found in this study (25.5 t ha^{-1}), while in Ecuador it was 40 t ha^{-1}. The blue water use per hectare estimated in this study is similar to the organic farms evaluated in Ecuador (5500 m^3 ha^{-1}) probably due to the lower yields of these farms.

Blue water use includes the extraction and production of raw materials used at the farm stage, in which 13% accounts for fertilizer production, 7% electricity generation (mainly hydroelectricity) and 1% due to packaging production. The high consumption of fertilizers is responsible for them being the second largest contributor to blue water use.

The greatest contributor to HTP and TETP impact categories was carbofuran, the active principle of some fungicides. Its contribution to these categories was 65% and 30%, respectively.

3.1.2. *Environmental indicators of Cavendish bananas at retail stores*

The results of bananas available at retail stores in this study considered bananas commercialized in São Paulo because of the importance of its market share due to the high populational density of Greater São Paulo. Nevertheless, Brazil has seven banana-producing regions throughout the country (Coltro; Karaski, 2014). Most of the bananas produced in Brazil are consumed near the production centers, except for Northern Minas Gerais and Bom Jesus da Lapa - BA regions whose distances from the consumers are approx. 1000 km. On the other hand, bananas consumed in São Paulo have the lowest environmental impact related to the

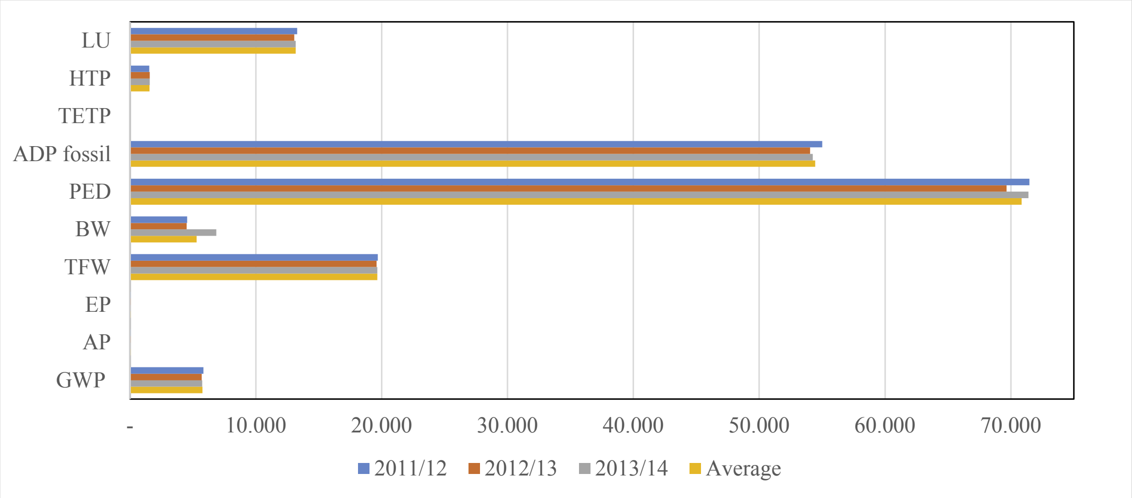

Fig. 3. Environmental indicators of Cavendish banana production in several crops.

transport stage since most of the bananas are produced in the Ribeira Valley region, which is the region with the shortest distance between production site and consumers (193 km).

Table 6 shows the life cycle impact assessment of Cavendish bananas taking into account 1 kg of bananas available at retail shops. The estimated GWP for Cavendish bananas available in the Brazilian retail market is 19%–48% higher than the estimated values for bananas produced in Costa Rica and Ecuador (excluding overseas transport and storage), which were calculated as 0.452 and 0.363 kg CO_2-eq kg^{-1} bananas based on studies by Svanes and Aronsson (2013) and Iriarte et al. (2014), respectively. The higher value regarding these studies is mainly due to the national transport stage, since the GHG emissions from the agricultural phase is of the same order of magnitude as those studies.

The farm stage was the greatest contributor to GHG emissions in this study, as well as in the studies developed in Costa Rica (49%) and Ecuador (53%), excluding overseas transport and storage considered in those studies (Svanes; Aronsson, 2013; Iriarte et al., 2014). The agricultural stage is responsible for the largest contribution to all environmental impact categories evaluated (from 40% to 95%).

The contribution of the packaging production stage to the categories of PED and ADP fossils is mainly due to the production of plastic packaging, while its contribution to the land use is mainly due to the wooden packaging because of reforestation to obtain the wood. However, this type of packaging is being replaced by plastic crates (returnable) and corrugated board boxes (recyclable). Corrugated board boxes are preferred by producers because they require less transportation as they are supplied as mountable cut sheets. On the other hand, returnable plastic crates need to be washed and sanitized before reusing them. In addition, plastic crates are more expensive than other packaging (wooden crates and corrugated board boxes), and they need to be managed by retailers to allow them to be returned. They also suffer losses due to theft. Thus, the change from 100% wooden crates to the situation analysed in this study of 22% wooden crates, 63% plastic crates and 15% corrugated board boxes led to reducing 90% of the use of land, total freshwater and blue water categories and 44% of primary energy demand and an increase in the HTP (510%), GWP (140%), acidification (110%), ADP fossil (76%) and eutrofication (40%) categories.

The contribution of the ripening stage to blue water use is due to electricity generation, which is predominantly hydroelectric in Brazil, and the production of ethylene that is used in the banana maturation chamber. In the case of electricity generation, water is not consumed but its use is accounted for in this impact category since it considers lake water and river water; both types of water used to produce hydroelectricity.

The transport stage showed the greatest contributions to the following environmental indicators: GWP, due to CO_2 generated by burning diesel; ADP fossil and PED, due to oil consumption to produce diesel; and acidification, due to SO_2 generated during diesel burning.

In the case of ADP fossils, the agricultural production stage presented the largest contribution to this environmental indicator due to the production of fertilizers, while plastic packaging

Table 6
LCIA results for **Cavendish banana available at retail shops** for the average of reference crops 2011/12, 2012/13 and 2013/14 (FU = 1 kg).

Environmental Indicator	Unit	Total	On farm (%)	Packaging (%)	Ripening (%)	Transport (%)	Retail (%)
GWP_{100}	kg CO_2-eq	0.537	52.13	6.93	2.31	24.16	14.47
Acidification	kg SO_2-eq	5.01E-3	71.32	2.43	13.32	12.93	0.00
Eutrophication	kg PO_4^{3-}-eq	3.52E-3	90.77	0.50	4.67	4.06	0.00
Total freshwater use	kg	1256.36	89.91	0.26	9.83	0.00	0.00
Blue water use	kg	488.71	71.32	0.58	28.68	0.00	0.00
PED	MJ	6.09	40.63	21.88	21.50	15.98	0.00
ADP fossil	MJ	4.10	49.31	22.15	5.66	22.88	0.00
TETP	kg DCB-eq	9.44E-4	93.63	6.32	0.01	0.04	0.00
HTP	kg DCB-eq	0.09	91.59	5.30	1.11	1.99	0.00
Land use	m^2 yr	0.707	94.85	4.94	0.01	0.00	0.00

GWP = global warming potential; PED = primary energy demand; ADP = abiotic depletion; TETP = terrestrial ecotoxicity potential; HTP = human toxicity potential.

production and fuel used in transportation are responsible for the contribution of packaging and transport stages to this indicator.

Bananas are stored and sold at room temperature and do not require packaging. Therefore, the retail stage contributed only to GHG emissions due to degradation of banana loss sent to landfill sites.

3.2. *Prata bananas at the farm gate*

Table 7 shows the main life cycle inventory inputs of the three crops of Prata banana cultivation stage evaluated in this study taking into account 1 ha of banana orchard. The total energy use and water use increased throughout the crops evaluated. The increase in the total energy is a consequence of the higher use of irrigation in the last crops due to the dry weather registered in 2012/2013 and 2013/2014, which needs electricity.

The water use was basically due to irrigation, which predominated in Prata banana cultivations in some of the farms evaluated in this study. The water use rose in the last crops due to the increase in the area of irrigated Prata banana plantations.

An aerial application of fungicides was also used in Prata banana cultivations in order to control the damage caused by fungus. On average, six applications of fungicides per year are carried out by light aircraft and ethanol is used as aviation fuel for aerial fumigation of the banana plantations.

According to the farmers, on average, 1.5 kg fertilizers plant^{-1} was applied every year, mainly urea, triple superphosphate and potassium chloride with different proportions of NPK. The use of nitrogen fertilizer in this study was of the order of 135 kg ha^{-1} or 6 kg t^{-1} bananas, which is approx. half of the amount used in the Cavendish banana cultivation, as shown in Table 4.

3.2.1. *Environmental indicators of Prata bananas at the farm gate*

Table 8 shows the life cycle impact assessment in the three crops of Prata banana cultivation stage evaluated in this study considering 1 ha of banana orchard. The average GWP obtained for the crops studied was 4484.92 kg CO_2-eq ha^{-1} or 208.70 kg CO_2-eq t^{-1} bananas produced, which is lower than the GWP value of 5762.00 kg CO_2-eq ha^{-1}or 226 kg CO_2-eq t^{-1} Cavendish bananas evaluated in this study (Table 5).

As shown in Fig. 4, approximately half of the GHG emissions are due to field emissions (44%), followed by fertilizer production (23%), packaging production (13%) and energy production (12%). The major contributor to GHG emissions in the field are direct and indirect N_2O emissions (0.022 kg CO_2-eq or 24%) due to the use of nitrogen fertilizer (urea) followed by CO_2 emissions (19%) also due to urea application (0.008 kg CO_2-eq), as well as limestone (0.009 kg CO_2-eq) used for soil remediation. Additionally, urea is responsible for 47% of emissions associated with fertilizer production.

The relative contributions to the GHG emissions of Prata banana production is in agreement with the results obtained for Cavendish bananas in this study and studies developed by various authors in Costa Rica and Ecuador, as shown in Fig. 2. The greatest difference between Prata and Cavendish bananas produced in Brazil is the contribution of the energy production, which represented 12% of the GHG emissions for Prata bananas compared to no contribution for Cavendish bananas as the latter has a small irrigated cultivation area (considering the farms evaluated).

Packaging production accounted for 13% of the GHG emissions and its major contributors are high density polyethylene – HDPE and corrugated board boxes used to pack the bananas for transportation with 40% and 30%, respectively. Plastic films used to cover the bunches of bananas contributed 18% to the GHG emissions, while 12% was due to wooden crates still used for transportation by some farms.

Burning diesel by agricultural machinery contributed 6% to the CO_2 emissions, while burning ethanol by airplanes for plant spraying contributed with only 0.02% due to its renewable source.

Regarding the other impact categories, no large variations among the values obtained for acidification and eutrophication potential were observed for the harvests evaluated (Fig. 5). A slight

Table 7
Life cycle inventory for **Prata bananas at the farm gate** for the reference crops 2011/12, 2012/13 and 2013/14 (FU = 1 ha).[a]

Parameter	Unit	2011/12	2012/13	2013/14
Energy				
Total	MJ	97,824.13	128,979.98	134,506.92
Electric (public grid)	MJ	21,353.58	32,642.72	34,791.81
Diesel	kg	77.19	85.83	92.89
Ethanol	kg	44.53	47.03	50.08
Non-renewable energy resources	kg	1209.12	1428.95	1492.72
Crude Oil	kg	483.66	546.98	572.09
Natural gas	kg	502.67	618.20	649.47
Other resources				
Water for washing bananas	kg	2602.90	3108.88	3313.35
Water for irrigation	kg	782,182.36	1,195,703.99	1,274,425.17
Fertilizers[b]				
N fertilizer (mainly urea 46% N)	kg	234.09	313.22	333.86
Phosphate fertilizer (45% P_2O_5)	kg	415.27	393.86	419.36
Potassium fertilizer (KCl 60% K_2O)	kg	1203.35	1296.54	1381.95
Micronutrients (Zn, Mn, Fe, Cu, B etc.)	kg	111.49	76.72	134.21
Correctives[b]				
Gypsum (natural gypsum)	kg	1342.55	1056.26	1125.56
Limestone (calcium carbonate)	kg	2085.53	2570.96	1805.16
Pesticides[b]				
Fungicides (sulfur based)	kg	25.40	24.92	26.56
Insecticides (imidacloprid)	kg	5.42	8.06	8.60
Herbicides (glyphosate)	kg	–	–	2.96
Mineral oil (for pulverization)	kg	81.77	99.89	106.46
Yield	kg	19,915	22,796	21,770

FU = functional unit.

[a] Weighted average for three farms.

[b] Active and filler elements.

Table 8
LCIA results for **Prata bananas at the farm gate** for the reference crops 2011/12, 2012/13 and 2013/14 (FU = 1 ha).

Environmental indicator	Unit	2011/12	2012/13	2013/14	Average
GWP_{100}	kg CO_2-eq	3993.02	4719.73	4742.02	4484.92
Acidification	kg SO_2-eq	37.04	48.78	52.03	45.95
Eutrophication	kg PO_4^{3-}-eq	28.08	36.47	38.10	34.22
Total freshwater use	m^3	27,903.11	32,901.08	35,424.48	32,076.23
Blue water use	m^3	11,648.05	15,833.33	16,919.69	14,800.36
PED	MJ	97,832.27	128,988.47	134,515.89	120,445.54
ADP fossil	MJ	46,484.28	55,204.44	57,832.26	53,173.66
TETP	kg DCB-eq	19.28	20.15	21.28	20.23
HTP	kg DCB-eq	2028.60	2086.26	2233.31	2116.06
Land use	m^2yr	13,688.94	14,669.29	15,562.83	14,640.36

GWP = global warming potential; PED = primary energy demand; ADP = abiotic depletion; TETP = terrestrial ecotoxicity potential; HTP = human toxicity potential.

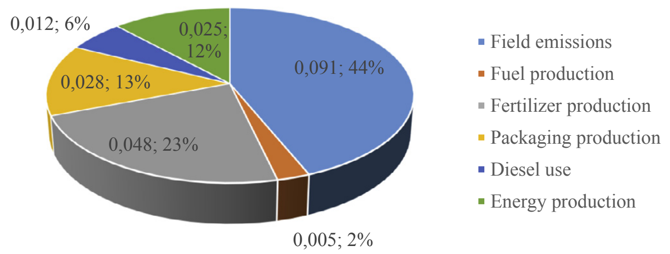

Fig. 4. GHG emissions for Prata banana production at farm level, average value for crops 2011/12, 2012/13 and 2013/14.

upward trend in the GWP, potential human toxicity and land use impact categories was observed for the most recent crops. However, a sharp increase in ADP fossils, PED, blue water use and total freshwater use was observed in the last harvest evaluated, which is mainly due to the higher use of electricity for irrigation of a larger area of Prata banana plantations. The greatest contributor to HTP and TETP impact categories was carbofuran, the active principle of some fungicides. Its contribution to these categories was 75% and 41%, respectively.

3.2.2. Environmental indicators of Prata bananas at retail shops

Table 9 shows the life cycle impact assessment of Prata bananas taking into account 1 kg of bananas available at retail shops. The estimated GWP for Prata bananas is 21% lower than Cavendish bananas available in the Brazilian retail market (Table 6), which is mainly due to the lower nitrogen fertilizer use and the lower transport distances from the producers to the wholesales and, consequently, the use of non-refrigerated trucks. The GHG emissions of Prata bananas is in the same range as the carbon footprint of Cavendish bananas produced in Ecuador (excluding overseas transport and storage), which was calculated as 0.363 kg CO_2-eq kg^{-1} bananas (Iriarte et al., 2014).

The contribution of the ripening stage to the environmental indicators of the Prata banana is much lower than the contribution of this step to the environmental indicators of the Cavendish banana (Table 6) because the Prata banana spends less time in the ripening chambers than the Cavendish banana to be suitable to sell. Therefore, it consumes less energy, which reduces the related emissions.

The contribution of packaging, transport and retail stages to the various environmental impact indicators follow the same profile as Cavendish, as discussed in Section 3.1.2.

The contribution of the retail stage to the GWP is lower than its contribution to the Cavendish banana supply chain due to the lower banana loss of Prata bananas at retail shops (7% - Prata vs 10% - Cavendish).

A comparison of the environmental indicators of both banana varieties evaluated in this study is shown in Fig. 6. As can be seen Cavendish bananas showed lower values for water use (TFW and BW), PED, toxicity indicators (TETP and HTP) as well as land use (LU). The highest differences among the indicators of these two bananas are PED and water use (TFW and BW), which are related to water and electricity use for irrigation.

4. Losses

Tropical fruits are fragile and highly perishable, therefore loss rates are significant. According to the FAO (2012), fruit and

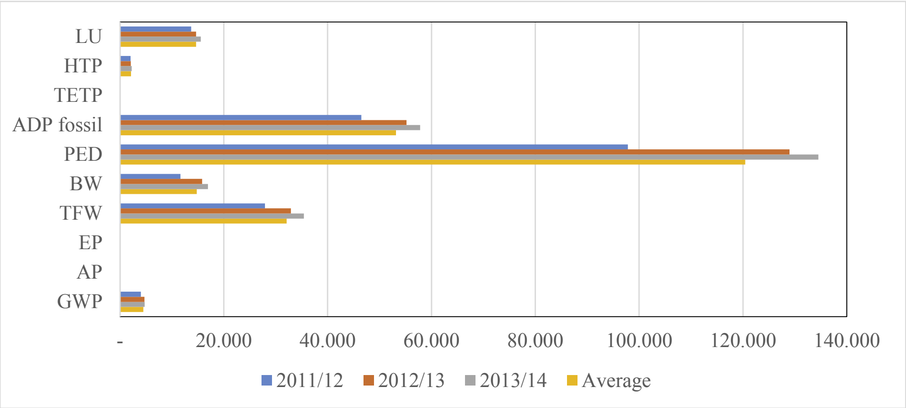

Fig. 5. Environmental indicators of Prata banana production in several crops.

Table 9
LCIA results for **Prata bananas available at retail shops** for the average of the reference crops 2011/12, 2012/13 and 2013/14 (FU = 1 kg).

Environmental indicator	Unit	Total	On farm (%)	Packaging (%)	Ripen (%)	Transport (%)	Retail (%)
GWP_{100}	kg CO_2-eq	0.423	51.20	7.65	0.95	28.22	11.98
Acidification	kg SO_2-eq	3.97E-3	56.71	9.23	6.21	27.84	0.00
Eutrophication	kg PO_4^{3-}-eq	2.27E-3	82.28	4.33	2.68	10.71	0.00
Total freshwater use	kg	1978.95	96.02	0.10	3.88	0.00	0.00
Blue water use	kg	971.10	91.39	0.47	8.14	0.00	0.00
PED	MJ	9.18	52.67	22.57	5.35	19.41	0.00
ADP fossil	MJ	4.67	44.85	17.44	1.71	36.00	0.00
TETP	kg DCB-eq	1.18E-3	95.51	4.44	0.01	0.04	0.00
HTP	kg DCB-eq	0.13	94.36	3.33	0.45	1.81	0.00
Land use	m^2.yr	0.855	97.70	2.29	0.01	0.00	0.00

GWP = global warming potential; PED = primary energy demand; ADP = abiotic depletion; TETP = terrestrial ecotoxicity potential; HTP = human toxicity potential.

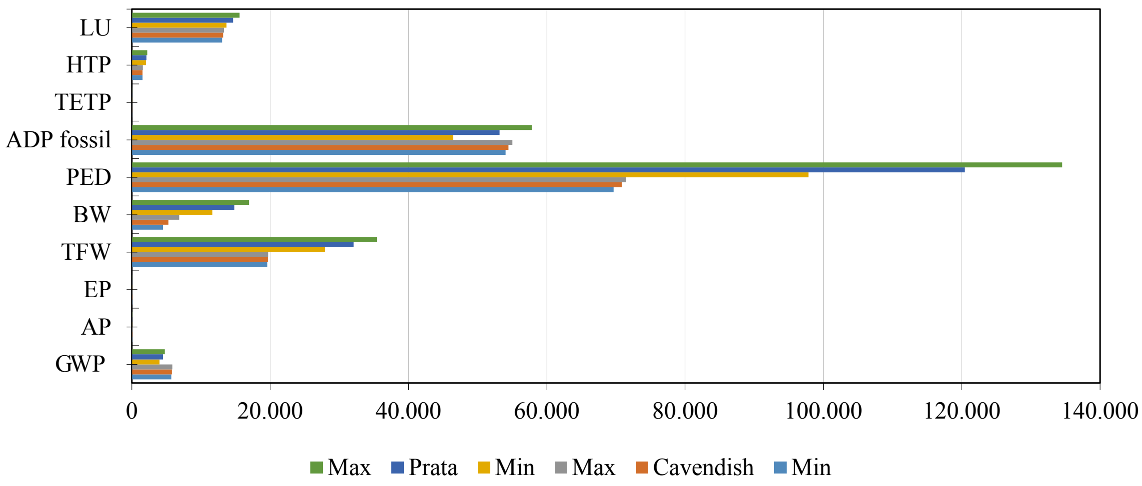

Fig. 6. Environmental indicators of both bananas evaluated in this study. The values of the three years were used.

vegetable losses in South America are approx. 40%. The main causes of wholesale losses are inappropriate packaging and storage, as well as precarious transportation. In retailing, the most serious problems associated with banana loss are the time between the purchase and sale of the fruit and the inadequate handling by the consumer (Salles, 2004).

According to primary data obtained in this study, banana loss throughout the supply chain was accounted for by 35.7% for Cavendish bananas and 25.5% for Prata, as shown in Table 10. At farm level, low quality bananas are sent to banana industries to produce jam, dehydrated bananas, dehydrated banana chips, etc. Loss of value due to inappropriate handling (mechanical damage, weight reduction, spots caused by insect attack, chilling, among other defects) was accounted for at wholesale storage, which is the highest throughout the productive chain. Maturation was the main cause of loss at retail shops. Therefore, a higher amount of bananas must be cultivated, ripened, stored and transported until the retailer in order to obtain 1 kg of bananas available on the market, which was accounted for in the system model. Nevertheless, no emissions were attributed to these losses as they have no or negligible commercial value, however the emissions of banana waste sent to landfill sites at the retail stage were taken into account in this study.

According to PENSA (Centro, 2008), a truck normally carries 400 boxes containing 17 kg of bananas per box. In this type of transport, the following weight losses occur: 7.5% female raquis, 3 to 5% crushed or damaged fruit due to handling bunches and inadequate transport, and 2.5% of fruit unsuitable for commercialization. However, in the data collected in this study, only 0%–1% losses were attributed to transport, which indicates that there has been an improvement in banana transport conditions in Brazil since the publication of the cited study.

Discarding bananas due to low quality as input in banana industries contributes to reducing the GHG emissions at the farm stage. Banana waste per hectare in this study was 1744.70 kg, which is lower than the study developed by Svanes and Aronsson (2013), who found 3240 kg ha^{-1}. GHG emissions avoided due to the landfill

Table 10
Banana losses throughout the production chain.

Life cycle stage	Loss (%)		Considerations
	Cavendish	Prata	
Farm	2.3	2.5	Low quality bananas sent to banana industries
Wholesale storage	23	15	Loss of value due to inappropriate handling
Retail	10	7	Loss due to maturation
	0.4	1	Bananas sent to employees for consumption as desserts
Total	35.7	25.5	Total banana loss throughout the chain

of this banana waste are 115.15 kg CO_2-eq ha^{-1}, based on the IPCC method (IPCC, 2006b), which means a reduction of 54,587 t CO_2-eq if we consider the area of bananas harvested in Brazil in 2016.

5. Discussion

Studies on banana production available in the literature mainly consider the carbon footprint or GWP as the environmental impact category, and therefore the other impact categories evaluated in the present study cannot be compared with banana production in other countries, but with other fruit. Most of the studies have a “cradle-to-gate” scope (from production to retail in Europe), except for Kilian et al. (2012) who considered the “cradle-to-grave” scope which also includes the consumption stage and the study developed by Svanes and Aronsson (2013), which took both scopes into consideration, i.e. “cradle to retail” scope (from production to retail) and “cradle to grave” scope (from production to consumption), including waste generated throughout the chain.

Craig et al. (2012) estimated the carbon footprint of bananas produced in Central and South America, and sold to the USA, at approximately 1 kg $CO_{2\text{-eq}}$ kg^{-1} bananas sold. The transportation stage showed the largest contribution (36%) of emissions by this supply chain, mainly due to overseas transport, followed by the farm production (22%) and retail (22%) stages.

Iriarte et al. (2014) estimated the carbon footprint of Ecuador's Premium bananas for export (Musa AAA – Cavendish) using a considerable amount of field data (harvests from 2009, 2010 and 2011). The authors adopted as system boundaries the stages from agricultural production to banana delivery at a destination port in Europe, considering two scenarios: the best-case scenario, where the refrigerated containers of the ships did not return empty from their trip to Europe and the worst-case scenario, where they returned empty. The carbon footprint of Ecuador's bananas for export ranged between 0.45 kg (best-case) and 1.06 kg $CO_{2\text{-eq}}$ kg^{-1} banana (worst-case). This study showed the importance of using efficient transportation, i.e. using containers to transport another product during the return trip accounted for the reduction in the carbon footprint by 57%. The study also concluded that the overseas transport stage has the highest contribution to the carbon footprint (from 27% to 67%) followed by agricultural production (from 23% to 53%).

Roibás et al. (2015) also evaluated the sustainability of Ecuadorian bananas, considering two indicators: the carbon footprint (CF) and water footprint (WF). Following the cradle-to-gate approach, the authors estimated the CF of bananas grown in conventional farms as 0.302 kg CO_2-eq kg^{-1} banana and a lower CF for bananas grown on organic farms, 0.249 kg CO_2-eq kg^{-1} bananas, mainly due to the higher amounts of nitrogen fertilizers applied in the former. This practice was also responsible for the higher grey WF of conventional farms (135 L kg^{-1} bananas) than organic farms (58 L kg^{-1} banana). On the other hand, the water use per kilogram of bananas at the farming stage (green plus blue WF) was higher in the organic farms (313 L kg^{-1}) than conventional farms (289 L kg^{-1}), mainly due to their lower yields of the former. The CF and WF calculated for the whole banana production chain until its final consumption in Spain were 1.28 kg CO_2-eq kg^{-1} banana and 490 L kg^{-1} banana at the consumers' hands, respectively. In this study, the farm stage was also identified as the second largest contributor to the CF, corresponding to 22% (after only the banana transport stage in Europe, with 31%) and the largest contributor to WF (83%).

Killian et al. (2012) estimated that bananas emit 1.09 kg of $CO_{2\text{-}}$eq kg^{-1} of exported bananas, with maritime transport accounting for 78% of emissions, followed by agricultural production at 15% and the distribution stage at 7%. Lescot (2012) calculated the carbon footprint of bananas exported to Europe as 0.85 kg CO2-eq kg^{-1} banana, in which the stages with the highest impact are overseas transport (43%), agricultural production (29%) and packaging (12%). Luske (2010) estimated the carbon footprint at 1.12 kg of CO_2-eq kg^{-1} exported bananas and also showed overseas transport and agricultural production stages with the greatest impact, whose contributions were 62% and 12%, respectively. Svanes and Aronsson (2013) estimated a carbon footprint (from farm-to-retail) of 1.37 kg of $CO_{2\text{-}}$eq kg^{-1} bananas and concluded that the hot spots were overseas transport stage, which accounted for approx. 55% of the carbon footprint, followed by the agricultural production stage, which accounted for 16%.

Table 11 shows a comparison of the results for GHG emissions for the farm stage of Cavendish bananas obtained from this study with results from studies conducted in other countries. Field emissions of the present study are similar to the value obtained in the study developed by Iriarte et al. (2014) in Ecuador, but this value is twice the value obtained in the studies developed in Costa Rica and higher than the study developed by Roibás et al. (2015) in Ecuador. These differences are probably due to variations in the application rates of nitrogen fertilizers and also the method adopted to assess the field emissions, which is responsible for estimating the N_2O emissions. The nitrogen fertilizer applied in this study was 238 kg N ha^{-1}, on average, which is similar to 265 kg N ha^{-1} reported in the study carried out by Iriarte et al. (2014).

The contribution of the fertilizer production and diesel use of the present study has the same order of magnitude of the studies carried out in Costa Rica and Ecuador. However, the contribution of spraying by airplane is much smaller in this study than in the studies carried out in Costa Rica due to two reasons: 1) fewer annual aerial sprayings of the plantations (10 aerial sprayings of the plantations evaluated in Brazil versus 25 aerial sprayings of the plantations evaluated in Costa Rica, as described by Iriarte et al., 2014), and 2) type of fuel used in aerial sprayings (in this study, ethanol was used as fuel, while aviation gasoline and jet propellant 1 were used as fuel in the studies conducted in Costa Rica, which have higher GWP than ethanol).

In this study, the contribution of overseas transport was not evaluated. However, its impact on the GWP of the Brazilian bananas exported to Europe should be of the same order as bananas produced in Ecuador (Iriarte et al., 2014) as the distance from Ecuador and Brazil to Europe is similar, i.e. 10,970 km (from Puerto Bolivar - Ecuador to Hamburg - Germany) and 10,570 km (Santos - Brazil to Hamburg - Germany).

Regarding to other environmental indicators, the results shown in Tables 6 and 9 obtained in this study are in agreement with the values published by Poore and Nemeck (2018), who built a multi-indicator global database on food's environmental impacts. Specifically for 1 kg bananas at retail, the estimated environmental impacts are 0.5–1.2 kg CO_2-eq, 0.2–2.8 m^2yr, 4–8 g SO_2-eq and 1–5 g PO_4^{3-}eq.

Comparing the environmental indicators obtained for Cavendish and Prata bananas in this study with the values obtained for apple and peach produced in North East Spain in the study developed by Vinyes et al. (2017), it was observed that GWP and land use are higher while acidification and eutrophication are lower for bananas in relation to apple and peach (Table 12). These differences are related to differences in crop yield (25.519 tons of Cavendish ha^{-1}, 21.494 tons of Prata ha^{-1}, 48.81 tons of apples ha^{-1} and 36.78 tons of peach ha¯1) besides differences in cultural practices adopted in these orchards (energy and diesel consumption, machinery use, fertilizers consumption, irrigation etc.).

In the case of toxicity indicators, lower values of human toxicity and greater ecotoxicity were observed for bananas in relation to apple and peach. These differences are probably due to the different

Table 11
Breakdown of GHG emissions of **Cavendish bananas at the farm stage** by different studies (kg CO_2-eq kg^{-1} banana).

	This study	Ecuador		Costa Rica	
		(2014)[a]	(2015)[b]	(2010)[c]	(2013)[d]
Field emissions	0.121	0.110	0.085	0.065	0.065
Fertilizer production	0.064	0.060	0.038	0.050	0.049
Packaging production	0.027	0.020	–	0.088	0.001
Fuel combustion	0.009	–	0.082	0.009	0.006
Spraying by airplane	4.0E-5	–	–	0.010	0.008
Fuel and electricity production	0.004	0.045	–	7.0E-4	–
Pesticide production	–	0.004	–	0.012	0.010
Landfill emissions	–	–	–	–	0,066
Animal and human labour	–	–	–	–	0.008
Total	0.226	0.240	0.274	0.138	0.220

[a] Iriarte et al. (2014).
[b] Roibás et al. (2015).
[c] Luske (2010).
[d] Svanes and Aronsson (2013).

Table 12
LCIA results for bananas obtained in this study versus apple and peach obtained in the study developed by Vinyes et al. (2017) (FU = 1 kg at retail).

Environmental indicator	Unit	Cavendish	Prata	Apple	Peach
GWP_{100}	kg CO_2-eq	0.537	0.423	0.229	0.286
Acidification	kg SO_2-eq	5.01E-3	3.97E-3	3.74E-2	4.71E-2
Eutrophication	kg PO_4^{3-}-eq	3.52E-3	2.27E-3	1.05E+1	1.07E+1
TETP	kg DCB-eq	9.44E-4	1.18E-3	3.24E-4	4.19E-4
HTP	kg DCB-eq	0.09	0.13	0.84	1.07
Land use	m^2.yr	0.707	0.855	0.335	0.433

GWP = global warming potential; TETP = terrestrial ecotoxicity potential; HTP = human toxicity potential.

types of pesticides used in these agricultural crops. The greatest contributor to HTP and TETP impact categories of the bananas evaluated in this study was carbofuran, the active principle of some fungicides. However, no data on the active ingredients of the pesticides used for apple and peach were available in the published paper. These environmental impacts of bananas can be reduced through changes in the application of this pesticide as shown by study developed by Castro et al. (2005), which evaluated carbofuran residues in Prata bananas submitted to nine different treatments of this pesticide. Carbofuran is used in the control of rhizome-borer, which is a serious problem in banana plantations, and can be found in all banana farms, regardless of the cultivar used. This pest promotes the partial destruction of the rhizome and, consequently, the reduction in the water and nutrients absorption by the plant, increase of the production cycle and reduction of the production of the plant, both in quantity and quality. The weakening of the plant favors the entry of the fungus *Fusarium oxysporum* f. sp *cubense* that causes the disease known as Mal-do-Panama.

In the study developed by Castro et al. (2005), carbofuran applications on the banana field were done during the banana cultivation according to Good Agricultural Practices (GAP) in order to correlate their effects with the residual levels of this carbamate in the fruits. In six of those treatments, 80 g $plant^{-1}$ of the commercial product were applied directly on the soil, as recommended by the manufacturer, while the other three applications were done in a smaller amount of carbofuran (only 15% of the quantity prescribed by the manufacturer or 12 g $plant^{-1}$) on cut plant. According to the authors, the pesticide applications on cut plant at lower concentration showed lower residual levels in the fruit (0.006–0.009 mg kg^{-1}) in relation to those treatments where a greater quantity of pesticide were applied on the soil (0.006–0.065 mg kg^{-1}). Therefore, the authors verified that its application on the cut plant (and not on the soil) represents an effective and cost-effective way of pesticide applying, besides minimizing the environmental effects and making this treatment more efficient and economical.

6. Conclusions

A set of ten environmental indicators of two banana varieties produced in Brazil were estimated using LCA applied to both Cavendish and Prata banana productive chains, which were GWP_{100} (or carbon footprint), water use (total freshwater and blue water), energy use (primary energy demand), use of resources (abiotic depletion potential), eutrophication, acidification, land use and toxicity (terrestrial and human). Although irrigation is not usual for banana production in Brazil, it is being adopted in productive areas that did not use irrigation due to the reduction of rainfall as a consequence of climate change. For this reason, water use was evaluated in this study.

The GHG emissions of Brazilian bananas at the farm gate were estimated, on average, at 5762 kg CO_2-eq ha^{-1} or 0.226 kg CO_2-eq kg^{-1} Cavendish bananas and 4485 kg CO_2-eq ha^{-1} or 0.209 kg CO_2-eq kg^{-1} Prata bananas. For bananas available at retail stores in the domestic market, 0.537 and 0.423 kg CO_2-eq kg^{-1} Cavendish and Prata bananas, respectively, were calculated. In both cases, the agricultural stage showed the greatest contribution, followed by transportation.

The total freshwater use at the farm stage was 19,646 and 27,903 m^3 ha^{-1} of banana orchard, but these values were reduced to 5300 and 11,648 m^3 ha^{-1} of banana orchard if only blue water use was considered for Cavendish and Prata bananas, respectively. However, the blue water use for 1 kg of banana available at retail stores in the domestic market was 489 and 971 L for Cavendish and Prata bananas, respectively.

Taking into account the farm stage, the results obtained in this study are in the same range as those found for Cavendish bananas produced in other countries. Taking into account the whole value chain, farm production was the major contributor to all the impact categories evaluated. The transport stage was the second greatest contributor for GWP, abiotic depletion potential (fossil) and acidification potential.

Therefore, the environmental indicators of banana production can be changed if improvements are made at the farm stage as this stage was the one that showed the greatest contribution to almost all the impact categories evaluated. A reduction in the use of nitrogen fertilizers, a reduction in the use of carbofuran-based pesticides through variation on the way of application and/or use of lower quantities of pesticide or change to other pesticides with less toxicity, use of cover crops, controlled irrigation use, proper management of ethylene, preference for transporting short distances without refrigeration and reduction of postharvest losses through improvements in post-harvest management (mainly handling) are some improvements throughout the whole value chain which could reduce the environmental impact of bananas.

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