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The carbon footprint of exported Brazilian yellow melon

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ABSTRACT

The carbon footprint of food has become important for producers worldwide as consumers and retail companies increasingly base their purchase decisions on carbon footprint labels. In this context, our objectives is to assess the carbon footprint (CF) of Brazilian yellow melon exported from the Low Jaguaribe and Açu region, including an uncertainty assessment, and to evaluate reduction potentials and improvement options. Exporting farms located in this region account for about 99 percent of Brazilian melon exports, mainly to the United Kingdom and the Netherlands. To determine the CF, we followed Life Cycle Assessment, according to ISO standards (14040 and 14044). The results are expressed in kg of CO_2-eq/t of exported melon. The production system encompasses processes in the Low Jaguaribe and Açu region (such as seedling, plant production, packing, and disposal of solid wastes from farms), upstream processes (including the production and transportation of inputs, such as seeds, plastics, and fertilizers), and downstream processes (melon transport). The total yellow melon CF in the reference situation is 710 kg CO_2-eq/t exported melon. However, scenario results indicate that this value can be reduced by 44 percent if melon fields are located in pre-existing agricultural areas, nitrogen fertilization is reduced, and no plastic field trays are used in melon production. GHG emissions from melon transport are relatively unimportant in the total CF. These results provide melon producers with an insight into the CF of their product, and options to reduce it.

1. Introduction

Agriculture accounts for about 10–12 percent of the total global anthropogenic emissions of greenhouse gases (GHG) (IPCC, 2007). This percentage increases when emissions related to deforestation and the production and transport of farm inputs (such as fertilizers, pesticides, and fuels) are included.

The burden of food production on climate change has been discussed in household food consumption studies that show differences in greenhouse gas intensities within food product categories (Sonesson et al., 2009; Audsley et al., 2009) and producing regions (Weber and Matthews, 2008). GHG emissions from the fruit sector have also been reported, mainly in the consideration of production systems that have been adopted in developed countries (Mouron et al., 2006; Audsley et al., 2009; Beccali et al., 2009, 2010).

Brazil is the world's seventh largest tropical fruit producer (FAO, 2011). The Brazilian national government has introduced low carbon agriculture policies and established emission reduction targets that require the agriculture sector to reduce their GHG emissions substantially (Federal law N° 12.187, 12/29/2009).

Brazilian food producers have invested in environmental product certifications as a way to differentiate their product on the external market. For example, fruit producers have provided certifications such as Eurepgap and Integrated Fruit Production (IFP) (Freitas et al., 2009). These certification schemes require comprehensive information and documentation regarding management practices, commitment to the social welfare of workers, and environmental sustainability. However, certification does not account for GHG emissions nor does it support management decisions that could reduce them.

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Carbon footprint (CF) protocols have been proposed to help producers account for and communicate the CFs of their products (Olofdotter and Juul, 2008). The CF of a product is defined as the amount of GHG expressed in terms of CO_2-eq or CO_2-equivalents emitted by that product during its entire life cycle, with specific system boundaries (Pandey et al., 2011).

Examples of CF protocols include PAS 2050 (BSI, 2011), which is used for certifying apple producers from New Zealand; the Product Life Cycle Accounting and Reporting Standard that was developed by the World Resource Institute (WRI and WBCSD, 2011); and the ISO/DIS 14067 – Carbon Footprint of Products, which is currently under development by the International Organization for Standardization (ISO, 2012). Despite diverging on system boundaries and the way results are presented, these standards consider GHG emissions from processes related to the life cycle of a product, allow the use of emissions factors presented by IPCC (2006) to estimate GHG emissions, and use global warming potentials for 100 years, according to IPCC (2006), to present the carbon footprint results in terms of CO_2-eq (Table 1).

The release of new requirements related to CF certification has raised the attention of Brazilian fruit producers interested in the global market. Carbon certification of melon production is especially relevant for Brazil because of the large share of melon in relation to the total export from the country. Melon export accounted for 22 percent of the sales of Brazilian fresh fruits in 2011 (128 million USD) (MDIC, 2011).

Few studies have assessed the CF of melon. Audsley et al. (2009) quantified the CF of melon produced in and outside of Europe in general terms, using proxy values from existing data related to similar food products. Cellura et al. (2012) quantified the CF of Italian melon produced in pavilion and tunnel greenhouses in a Sicilian agricultural district. However, these studies do not address melon production in tropical countries such as the market leader, Brazil. Neither do these studies examine the emission reduction potential of possible improvement options nor do they analyze the uncertainties in the CF calculations of melons planted in open fields.

Therefore, our objective is to assess the CF of exported Brazilian yellow melon by considering the uncertainties in the GHG emissions and to evaluate reduction potentials of improvement options. The CF is assessed following a life cycle approach. Results give melon producers insight into the CF of their product with potential options to reduce the CF. However, a broader assessment measuring other emissions to air, water, and soil, and their regional and global impacts shall be undertaken to understand all environmental issues related to this product.

2. Melon production in Brazil

Melon (*Cucumis melo* L.) is a cucurbit crop whose fruit is rich in vitamins (116 μg A, 40 μg B1, 30 μg B2, and 29 mg C in 100 g of melon), minerals (429 mg K in 100 g of melon), and has a low calorie content (30 kcal per 100 g) (CNPH, 2011). Melon is produced primarily in tropical regions and subsequently exported across the world (FAO, 2011).

Brazil was the second largest world melon exporter in 2009 (FAO, 2011). Brazilian melons are mainly exported (98 percent) to

Table 1
Main methodological issues according to PAS 2050 and WRI/WBCSD.

Issue	PAS 2050	WRI/WBCSD
Scope	Attributional Life cycle assessment (LCA): - Cradle-to-gate (business to business). - Cradle-to-grave (business to consumer).	Attributional Life cycle assessment (LCA): - Cradle-to-gate (intermediate products, that is, products used to produce other products). - Cradle-to-grave (final products, used by the consumer).
Impact assessment	Global warming potential for 100 years, according to IPCC (2007).	Global warming potential, for 100 years, according to IPCC (2007).
Indicator	CO_2-eq/functional unit.	CO_2-eq/functional unit.
System boundary	The following processes show be included: transformation of raw materials, energy production and use, production of capital goods (e.g., machinery and buildings), operation of premises (e.g., facilities lighting, air conditioning), manufacturing, transport, storage, use, and final disposal.	The following processes show be included: transformation of raw materials, energy production and use, manufacturing, transport, storage, use, and final disposal.
GHG	- GHG inventoried: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) emissions to, and removals from, the atmosphere. - CO_2 emissions from biogenic sources equals removals and shall not be considered.	- GHG inventoried: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) emissions to, and removals from, the atmosphere. - All biogenic and non-biogenic emissions and removals shall be reported separately, as well as emissions from land use change.
Land use change	- Consideration of direct land transformation from forest to agricultural land occurring after 1990 and caused by any stage of the product life cycle. - Biogenic CO2 emissions are calculated by allocating 1/20 of carbon stock losses or a removal to each year after transformation occurs. - Carbon removal in soils from changes in agricultural practice is not considered.	- Consideration of direct land transformation from forest to agricultural land occurring after 1990 and caused by any stage of the product life cycle. - Biogenic CO2 emissions are calculated by allocating 1/20 of carbon stock losses or a removal to each year after transformation occurs. - Carbon removal in soils from changes in agricultural practice can be considered if scientifically proven.
Carbon storage in products	Consideration of biogenic and non-biogenic carbon removal in products, if during their final disposal the carbon content is preserved for more than one year.	Consideration of biogenic and non-biogenic carbon removal in products, if during their final disposal the carbon content is preserved for more than one year.
Data quality	- Inventory data shall be reliable, timely, represent all processes, and technologically, geographically, and statistically representative. - Primary data shall be collected for all processes owned, operated, or controlled by the organization developing the study. - Emissions may be calculated or estimated using factors presented by IPCC (2006) or national inventories.	- Inventory data shall be reliable, timely, represent all processes, and technologically, geographically, and statistically representative. - Primary data shall be collected for all processes owned, operated, or controlled by the organization developing the study. - Emissions may be calculated or estimated using factors presented by IPCC (2006) or national inventories.
Allocation	Suggest economic allocation, if it cannot be avoided by product system expansion.	Suggest physical allocation, if it cannot be avoided by product system expansion.

Sources: BSI (2011) and WRI and WBCSD (2011).

European countries: 28 percent to the United Kingdom and 42 percent to the Netherlands (MDIC, 2011). The export predominantly occurs between September and February when production at Spanish farms is low (Funcke et al., 2009).

The main exporting melon producers in Brazil are clustered in the Low Jaguaribe and Açu region, in the northeastern states of Ceará and Rio Grande do Norte. In 2009, melon production in this region contributed to 99 percent of the country melon exports (MDIC, 2011).

The high luminosity (about to 3000 h/year), low precipitation rate (from August to December) and humidity, and availability of irrigation water during the dry season constitute excellent conditions for melon production in the Low Jaguaribe and Açu region. Between 1999 and 2009, the melon cultivation areas in these regions increased by more than 60 percent (IBGE, 2010).

The type of melon commonly produced and exported belongs to the *C. melo* inodorous Naud group, which is commonly known as yellow melon. This fruit has a yellow husk, whitish pulp, sugar content between 8 and 12° Brix, an average weight of 1.5 kg, and a production cycle between 65 and 75 days. This melon is disease resistant, unaffected by transport, and remains at quality within the average post-harvest life of one month (Silva and Costa, 2003).

In the studied region, melon production occurs in open fields and relies on drip irrigation and fertirrigation (that is, application of soluble fertilizer through an irrigation system). Fertirrigation is required because of insignificant rainfall during the production period (from July to December) (Miranda et al., 2008) and a low nutrient content of soils (Crisóstomo et al., 2002). Farms generally import melon seeds, agrochemicals, soil cover plastics, and packing materials from abroad because national legislation (Port RFB/Secex n° 1/2009) prescribes reduced taxes for imported materials for producing export fruits.

3. Research method

The CF of melon assessed in this study is based on life cycle assessment – LCA (ISO 14040 and 14044, 2006a,b) and focuses on the climate change environmental impact category.

3.1. Scope

3.1.1. Functional unit

The functional unit is one tonne of exported yellow melon. According to data gathered at selected Brazilian melon farms, the production of one ton of yellow melon requires 3.64 kg of seedlings and 0.034 kg of seeds.

3.1.2. System boundary

The system boundary is presented in Fig. 1 and includes (i) upstream processes – that is, the production and transport of inputs, such as seeds, fertilizers, pesticides, diesel, and plastics; (ii) processes in the Low Jaguaribe and Açu region – that is, the production of seedlings, melons, and the packing and disposal of solid wastes from farms; and (iii) downstream processes – that is, the transport of melons to Europe. Hazardous wastes generated by melon farms are assumed to be incinerated and regular wastes (such as plastics) are assumed to be deposited in landfills. Melon distribution by European retailers and the final consumption of the melons lie beyond the scope of this study.

3.1.3. Allocation procedure

Allocation of inputs and outputs based on the market price of exported and nationally commercialized melons was performed. The allocation procedure considered that the value of exported melon is USD 0.6/kg (99 percent of total revenue), and the value of nationally commercialized melons is USD 0.1/kg (1 percent of total revenue).

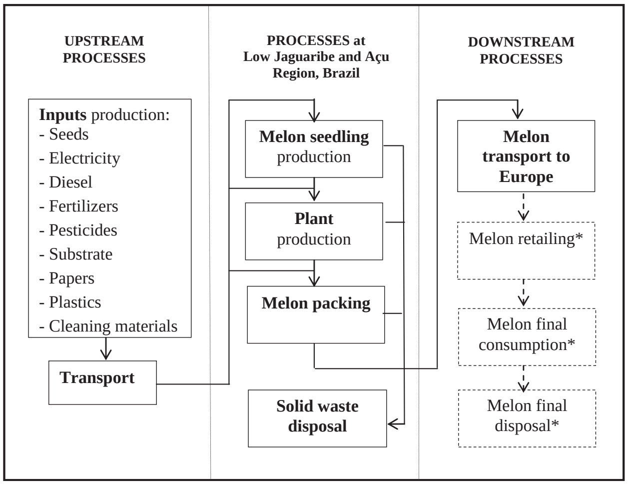

Fig. 1. System boundary of the yellow melon production chain.

3.2. Inventory analysis

3.2.1. Data quality

Inventories of melon production processes are not available in the Brazilian life cycle database that is currently under development. The main inventory initiatives have focused on hydroelectricity, transports, and diesel.

Primary data from seedlings, plant production, and melon packing were obtained in production units located in the Low Jaguaribe and Açu region, (4°20′30″–5°30′00″S and 37°05′00″–38°30′00″W), the largest melon-exporting region in Brazil. Three melon farms and three packing houses located in this region were the sources of primary data regarding plant production. These three farms accounted for 23 percent of the total melon exports in 2010.

Because Brazilian melon farms typically import their melon seeds, no seed farms exist in the studied region and little information regarding this process is available in the literature. To overcome this limitation, primary data was collected at the melon seed experimental station that belongs to Embrapa Agroindustry, Fortaleza, Ceará, Brazil.

A structured questionnaire was distributed to melon producers in 2011 to obtain primary data. The questionnaire consisted of tables containing lists of inputs used in each stage of the process and related blank cells to be filled in by interviewees with the amount of all inputs per ton of melon produced. Farmers answered questions concerning the average consumption of materials, water, and energy at their farms.

Secondary data from the remaining upstream and from downstream processes were obtained from the Ecoinvent database (Frischknecht and Jungbluth, 2007).

3.2.2. Data collection in melon farms and packing houses

3.2.2.1. Seed production. Brazilian farms generally import seeds from the United States, Argentina, and Chile (MDIC, 2011) because seeds are not produced commercially in Brazil. Therefore, data on seed production was collected from an experimental seed greenhouse maintained by the Brazilian Agriculture Research Corporation (Embrapa). In this experimental station, seeds are produced in non-heated greenhouses, a process that includes the following steps: seedling and melon production, harvest, seed extraction, seed fermentation, seed washing, seed drying, and storage. To determine the amount of resources used in seed production, we assume that the greenhouse, with 0.05 ha, produces 1632 melons per year; each melon seed results in a viable seedling; harvesting occurs after 60 days from seedling transplantation, with melons weighting 1 kg and containing 400 viable seeds; four seed production cycles occur in one year; the lifespan of used materials is three years for the greenhouse plastic structure, 900 days for the seedling trays (polyethylene terephthalate – PET), and two years for the coconut substrate.

3.2.2.2. Seedling production. Data was collected at a production unit in the Low Jaguaribe and Açu region. In this unit, seedling production consists of the following steps: sowing, germination in controlled temperature, and seedling development in greenhouses. To determine the amount of resources used in seedling production, we assume that a greenhouse, with 0.12 ha, produces 110 million seedlings per year; the lifespan of the greenhouse plastic is three years; and the lifespan of seedling trays (PET) is 900 days.

3.2.2.3. Plant production. Commercial melon production occurs in open fields between July and January, during the dry season. Production includes five steps: soil preparation, transplanting of seedlings, management, harvest, and cleaning of fields. Polyethylene mulching is used to reduce water evaporation from the soil and to prevent putrefying of forthcoming fruits when touching moist soil. Seedlings are transplanted and covered with fabrics, made from polypropylene, that prevent pests during the first 25 days, before pollination starts. Crop management begins with daily fertirrigation, and disease and pest control. Field trays may or may not be used to prevent the contact of fruits with soil. After harvest, crop residues are ploughed.

We collected data from three producers, all located in the studied region, during the first semester of 2011. This data refers to average amounts of inputs and wastes observed in previous harvests.

To determine the amount of resources used in plant production from this survey, we assume that the average harvested production of 1 ha (open field), with 12,000 melon plants, is 23 t; the average production cycle is 70 days; and the lifespan of used materials is 140 days for mulching (low density polyethylene), 420 days for the field trays (PET), 210 days for the fabric (polypropylene), and 210 days for the irrigation tubes (low density polyethylene).

One of these farms provided data on synthetic fertilizer and water use for 35 melon plots. Farms interviewed represented 23 percent of the total melon export in 2010.

The amount of solid waste produced was quantified by weighting plastic and metal wastes on farms. The total weight of empty pesticides packages was calculated by multiplying the number of packages used by their average mass. The number of packages used was estimated by dividing the average amount of pesticide used on the farm by the amount in a full pack.

3.2.2.4. Melon packing. After harvesting, melons are sent to packing houses located near the crop fields, where they are classified as fruit for export or for sale on the domestic market (commercialized as fruit or animal feed). Exported melons usually have an acceptable sweetness level (soluble solids between 10 and 12° Brix).

The packing of melons occurs with high sanitary control in order to prevent insect proliferation and to guarantee a post-harvest lifetime of 30 days. In the packing houses, melons are initially washed and dried, protected with the application of fungicide in the peduncle region, sorted by weight and size, organized in pallets, and wrapped using plastic tapes and corners. Pallets are stored at room temperature before being organized in refrigerated containers and shipped. To determine the amount of resources used in melon packing, we assume that the packing house, sized at 4500 m^2, has the capacity to sort and pack 43 t melon/day; the packing house is used for nine months of the year; and corrugated cardboard boxes with double walls have the capacity to pack 10 kg of melons.

3.2.3. Calculation of transport distances

Materials purchased by melon producers may be produced in different Brazilian states or even in other countries. We define two situations to calculate transport distances of farm inputs: national and international production of inputs. In the first situation, the average of transport distances from different production states to Low Jaguaribe and Açu region are weighted by each state's share in the total national production (IBGE, 2010). In the second case, the distance equals the average of distances from each country that exports the necessary materials to Brazil, weighted by each country's share in the total national import (MDIC, 2011).

We assume that imported farm inputs and exported melons are transported by ships, whereas national farm inputs are known to be transported by trucks. Transport from ports to farms and from farms to ports are also assumed to be by truck. According to the information obtained from the farm producers, these trucks generally have a capacity of 24 t. Transportation of melons by ships is assumed to occur in refrigerated containers of 20 t, from the Pecém sea port in Ceará to the Rotterdam port in the Netherlands (7465 km).

3.2.4. Estimation of GHG emissions

3.2.4.1. Emissions of GHG per activity in melon farms and packing houses. According to IPCC (2007), some gases have a relatively direct and certain global warming potential (GWP), while other gases have a relatively uncertain and indirect global warming effect. We include GHG with a direct GWP in this study.

To estimate GHG in seeds, seedlings, melon production, and packing, the following activities are included: land use change (that is, biomass loss from cutting and burning, and soil organic matter mineralization); nitrogen fertilization (including incorporation of field residues in soils); and fossil fuel combustion by tractors. These activities may release CO_2, CH_4, and N_2O (Fig. 2).

Eqs. (1a) and (1b) are used to estimate the mass (g) of GHG emitted by the following processes: seed, seedling, and melon plant production, and packing. Initially, the annual mass (kg) of greenhouse gas g (CO_2, CH_4 and N_2O) emitted during activity a (land use change, nitrogen fertilizer application, or fossil fuel burning) is calculated ($GHG_{g,a}$ in Eq. (1a)). $GHG_{g,a}$ is obtained by multiplying the annual mass (kg) of resource used (or removed, in the case of vegetation) during activity a ($Input_a$) by the emission factor ($EF_{g,a}$). When the activity is biomass removal, the type of vegetation and soil prevailing in the Low Jaguaribe and Açu region is considered when choosing the emission factor, considering IPCC (2006) and Brazilian GHG Inventory (MCT, 2010a).

In sequence, the emissions of GHG g from all activities are added up to estimate the total mass of GHG g emitted in a certain process ($Process\_GHG_g$ in Eq. (1b)). The equations and emission factors used to estimate each gas by activity are presented in Annex A.

$$GHG_{g,a} = Input_a * EF_{g,a} \tag{1a}$$

$$Process\_GHG_g = \sum_{a=1}^{3} GHG_{g,a} \tag{1b}$$

3.2.4.2. Emissions from other processes. GHG emissions from the production of other inputs (agrochemicals, diesel, electricity, substrates, and cleaning materials), from transport of inputs and

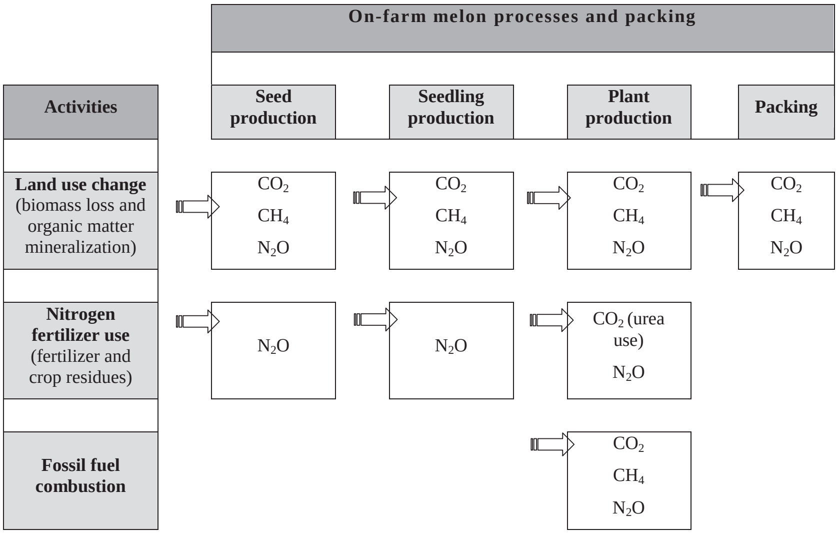

Fig. 2. Sources of emissions of GHG per activity in on-farm melon processes and packing.

melons, and from the final disposal of solid wastes were accounted using the Ecoinvent database (Frischknecht and Jungbluth, 2007). Emissions from the production of coconut substrate were estimated based on Figueirêdo et al. (2010).

3.3. *Impact assessment*

The CF of each process is quantified considering the mass (kg) of GHG emitted in each activity and their respective GWP, according to IPCC (2006). In Eq. (2), CF_p is the carbon footprint of process *p* (kg CO_2-eq t melon^{-1}.year^{-1}), $Process\_GHG_{g,p}$ is the total amount (kg) of greenhouse gas g emitted from process p, and GWP_g is the global warming potential of greenhouse gas g, over a timeframe of 100 years.

$$CF_p = \sum_{g=1}^{n} Process\_GHG_{g,p} * GWP_g \tag{2}$$

3.3.1. *Scenario and uncertainty analysis*

We defined a reference situation to quantify the use of inputs, generation of solid waste, GHG emissions, and CF of the yellow melon. This reference situation has the following characteristics:

- Less than 20 years ago, Savanna (Caatinga) forests occupied the area where seedling and melon production currently takes place, as well as where packing houses are now located; forest cutting and burning occurred just before melon fields were established. Even though more than 90 percent of the melon fields on the surveyed farms were installed on former agriculture fields, the Low Jaguaribe and Açu region has experienced significant growth in melon production (63 percent from 2000 to 2006). In this sense, land transformation was considered in the reference situation.
- Seeds, fertilizers, papers and plastics used in melon seedling, plant production, and packing are mainly produced abroad, transported to the port by ship and to farms and packing houses by truck (as currently done on two of the farms surveyed);
- The amount of nitrogen fertilizer applied in melon production fields is 6 kg N/t melon (average value of the three farms surveyed);
- Plastic field trays are used in plant production to prevent melon contact with mulching (as found in one of the farms surveyed).

GHG emissions may vary among farms depending on farm practices. Therefore, the sensitivity of the calculated CFs was tested to variations in the production process. The most important variations in production practices in melon farms that potentially reduce GHG emissions were identified. These variations were used to define five different scenarios (Table 2). The following facts reported by farmers in the Low Jaguaribe and Açu region were considered when defining these scenarios:

- Scenario 1 (use of 4 kg N/t melon): The amount of mineral nitrogen applied and the obtained yields differ considerably among farms. For instance, according to the data provided by a melon farmer overseeing 35 plots, productivity of 28 t/ha was reached at mineral nitrogen fertilization rates ranging from 2.5 to 4.5 kg N/t of melon (Fig. 3). Thus, lower nitrogen fertilization results in equally good productivity as high nitrogen use. Furthermore, research by Crisóstomo et al. (2002) on fertilization of melon fields in the same region indicated that, on

Table 2
Characteristics of the reference situation and scenarios for melon production in Brazil.

Characteristics	Scenarios					
	Ref	1	2	3	4	5
Land conversion						
• Deforestation for seedling, plant production, and packing house.	X	X		X	X	
• No deforestation, but seedling and melon production on agricultural land, and packing in constructed area.			X			X
Mineral nitrogen fertilizer						
• Average fertilizer use (6 kg N/t melon)	X		X	X	X	
• Reduced fertilizer use (4 kg N/t melon)		X				X
Transport of fertilizers, papers, and plastics						
• From abroad to Brazilian port by ship, and from port to farms and packing houses by truck.	X	X	X		X	X
• From national producers to farms and packing house by truck.				X		
Field trays in plant production to prevent contact of fruits with soil						
• Use	X	X	X	X		
• No use					X	X

average, 25 t of melon/ha is obtained when 100 kg of mineral nitrogen per hectare is applied (i.e. 4 kg N/t melon, ranging from 3 to 5 kg N/t of melon). Thus, the reduction of nitrogen fertilizer from 6 to 4 kg N/t of melon is a reasonable carbon reduction option;

- Scenario 2 (no deforestation): some melon farms occupy former agricultural areas used to cultivate other crops more than 20 years ago;
- Scenario 3 (transport of materials by truck): Importing materials with reduced taxes is allowed by law when the final product is exported. However, some melon farms and packing houses acquire all materials on the national market. These materials are usually produced in the southeast states and then transported to melon farms by truck;
- Scenario 4 (no use of plastic trays): According to some farmers, plastic trays are necessary when melon fields are located in clay soils that retain water for long time periods. Higher soil humidity usually damages the fruit skin, thus reducing its market value. Soils used to cultivate melons in the studied region range from arenosol to high clay activity. Thus, the use of plastic trails is not always necessary;
- Scenario 5 (best case): This scenario occurs in one of the researched melon farms. This farm is located in former agricultural fields, applies on average 4 kg N/t, and does not use plastic trails, with average productivity of 23 t/ha in 2010.

The CF was calculated for each scenario. Additionally, the uncertainty in each scenario was analyzed using Monte Carlo analysis, assuming log normal distributions of probability functions. The Pedigree matrix was used to determine the deviations of each parameter (Goedkoop et al., 2008).

4. Results and discussion

4.1. Inputs used and solid waste generated in on-farm and packing processes

Table 3 presents the primary data collected in the experimental seed production greenhouse and production units located in the Low Jaguaribe and Açu region. Melon (plant) production requires most of the inputs and generates the largest amount of solid waste among these processes. However, this picture changes if these processes are compared on the same production mass base (one ton of seed, seedlings, melons, and exported melons). Then seed production is the number one process in terms of land, energy, and material use as well as waste generation.

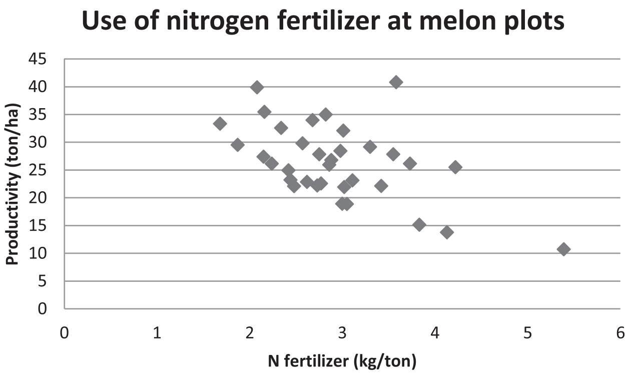

Fig. 3. Use of nitrogen fertilizer and productivity obtained in melon plots.

Table 3
Primary data obtained from melon farmers and researchers at an experimental melon seed greenhouse, related to 1 t of exported melon.

Inputs and outputs	Unit	Seed production	Seedling production	Plant production	Melon packing
Area	m^2	0.30	0.01	441.92	0.52
Seed	g	0.08	33.66	0.00	0.00
Seedling	g	9.03	0.00	2471.75	0.00
Coconut substrate	g	1011.11	3564.00	0.00	0.00
Water	L	0.09	0.06	186.05	0.15
Electricity	kWh	11.49	0.46	72.60	18.15
Diesel	g	0.00	0.00	7207.20	0.00
Cleaning products	g	0.00	0.00	0.00	648.10
Plastics	g	73.27	519.31	38008.36	659.01
Papers	g	0.00	0.00	0.00	58495.80
Wood (pallets)	g	0.00	0.00	0.00	11965.80
Fertilizers					
Organic compost	g	0.00	0.00	123684.66	0.00
N	g	4.05	1.65	5548.72	0.00
P_2O_5	g	0.59	1.65	6660.24	0.00
K_2O	g	7.47	0.00	9613.66	0.00
Others	g	3.98	0.00	2347.80	0.00
Pesticides					
Insecticide	g	1.28	0.01	765.72	0.00
Fungicide	g	0.55	0.02	480.19	2.66
Herbicide	g	0.46	0.00	0.00	0.00
Solid waste					
Plastic	g	66.01	523.47	38008.36	0.00
Empty pesticide packages	g	0.16	0.00	643.50	0.31

4.2. GHG emissions in the reference situation

The export of one ton of yellow melon generates the average total amount of 509,419 g of CO_2, 1430 g of CH_4, 482 g of N_2O, and 30,238 g of other GHG (Table 4). The overall emission from upstream and downstream processes is higher than the overall emissions from on-farm and packing processes in the Low Jaguaribe and Açu region. Upstream and downstream processes together contribute 63 percent of CO_2, 85 percent of CH_4, 55 percent of N_2O and 100 percent of all other GHG emissions. However, consideration of the individual processes in the yellow melon chain shows that plant production generates the largest emissions of CO_2 (37 percent). The production of fertilizers is the largest source of CH_4 (71 percent) and N_2O (53 percent).

Land conversion (from Caatinga vegetation to melon production) is the major source of CO_2 emissions, even when distributing these emissions over 20 years in seedling and melon production farms, and in packing houses. In the reference situation and in scenarios 2, 4, and 5, the removal of Caatinga vegetation was assumed, causing CO_2 emissions from biomass loss. The organic matter in the soil is mineralized into CO_2 and N_2O emissions. The burning of biomass after land conversion releases CO_2, N_2O, and CH_4 as well. The use of urea ($CO(NH_2)_2$) in plant production also results in CO_2 emissions related to the formation of bicarbonate after soil moisturizing (IPCC, 2006).

Nitrous oxide emissions result from the burning of biomass after land conversion, from fossil fuel burning, and from fertilizer application (mainly inorganic). Fossil fuel is used only in plant production. The application of fertilizers occurs in melon seed, seedling, and plant production, leading to the emission of N_2O related to the nitrifying and denitrifying bacterial activity in the soil. Crop residues, remaining on melon fields after harvestings are

Table 4
Estimated GHG emissions of 1 ton of exported yellow melon.

Processes	Reference situation							
	CO_2 (g)	%	CH_4 (g)	%	N_2O (g)	%	Other GHG[a] (g)	%
Packing	201.96	0%	0.30	0%	0.03	0%	0.00	0%
Plant	187375.32	37%	215.82	15%	217.80	45%	0.00	0%
Seedling	3.96	0%	0.01	0%	0.04	0%	0.00	0%
Total	187581.24	37%	216.13	15%	217.87	45%	0.00	0%
Seed production	106.92	0%	0.10	0%	0.10	0%	0.00	0%
Transport of melon BR-NL	60100.17	12%	0.35	0%	1.73	0%	67.67	0%
Paper production	52058.96	10%	5.78	0%	3.70	1%	109.22	0%
Plastic production	89301.73	18%	2.39	0%	0.97	0%	496.99	2%
Production of fertilizers	47570.40	9%	1013.54	71%	253.68	53%	2378.72	8%
Production and distribution of electricity	17885.73	4%	167.78	12%	0.81	0%	16.97	0%
Transport of materials to farms	22544.48	4%	0.14	0%	0.63	0%	23.32	0%
Other processes[b]	32269.12	6%	23.98	2%	2.79	1%	27144.80	90%
Total upstream and downstream processes	321837.51	63%	1214.05	85%	264.42	55%	30237.70	100%
Total emissions	509418.75	100%	1430.18	100%	482.29	100%	30237.70	100%

[a] Other GHG: GHG excluding CO_2, CH_4, and N_2O according to IPCC (2006).

[b] Other processes: all other processes considered in the system boundaries (Fig. 1) that are not nominated in this table.

incorporated to the soil, also result in the emission of N_2O when the organic matter is mineralized.

Methane emissions occur when biomass is burnt after land conversion and when diesel was burnt by tractors in plant production fields.

4.3. *CF in the reference situation and alternative scenarios*

The average CF of yellow melon in the reference situation is 710 kg CO_2-eq/t exported melon (Fig. 4). This average value is reduced by 6 percent if the nitrogen application is brought back from 6 to 4 kg N/t of melon (Scenario 1). Locating melon on-farm and packing processes in the Low Jaguaribe and Açu region in pre-existing agricultural areas reduces CF by 24 percent (scenario 2). Eliminating plastic field trays from plant production reduces CF by 13 percent (Scenario 4). On the other hand, the CF increases by 5 percent if all transportation of inputs occurs by truck from production sites located in main production regions in Brazil (scenario 3). In scenario 5, the reduction potential of all measures combined is 44 percent.

In the reference situation and all scenarios, the CF from upstream (production and transport of inputs) and downstream processes (transport of melons) exceed the CF from processes in the Low Jaguaribe and Açu region (Fig. 5). The production of fertilizers and plastics together has the largest share in the overall CF in the reference situation and in most scenarios. Reducing the use of these inputs also decreases the overall CF of the production chain.

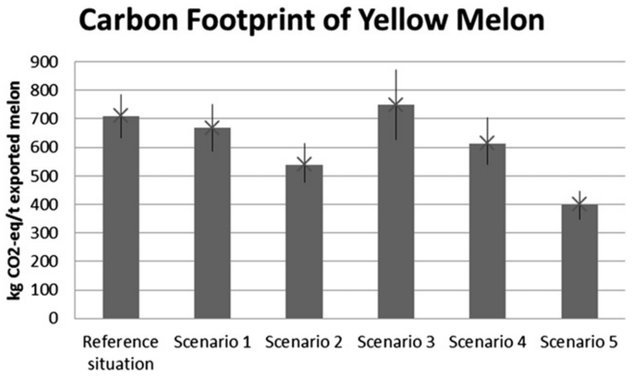

Fig. 4. Yellow melon CFs by scenario, including estimated uncertainty.

Melon seed and seedling production accounts for less than 1 percent of the total CF in all scenarios. The main processes related to seed production and contributing to the CF at this stage are the production and distribution of electricity (mostly required by the oven-drying) and the production of plastics (mainly disposable plastic cups used to ferment seeds) (Fig. 6). In melon seedling, the production of plastic trays and their transport to the seedling farm are the main processes contributing to the CF up to this stage.

Plant production has a relatively large share in the CF in most of the scenarios (Fig. 5). Plant production contributes up to 258 kg CO_2-eq/t of exported melon when land is converted from forest to melon fields and the average amount of nitrogen fertilizer is used (reference situation and scenarios 3 and 4). The inputs used in plant production where manufacturing emits the highest amount of GHG are fertilizers and plastic (Fig. 6). The main kind of fertilizer is nitrogen, in scenarios 2, 3, and 4, and organic compost, in scenarios 1 and 5. The main types of plastic used are PET (field trays) and low-density polyethylene (mulching).

Melon packing only makes a considerable contribution to the total CF in the reference situation and scenarios where land transformation from forest to packing house was assumed (scenarios 1, 3, and 4). Paper materials for corrugated cardboard and trays are used to pack melon; their production and transport emit GHG (Fig. 6). Thus, these processes need priority when trying to minimize the CF in packing houses.

The distances between input production sites and melon fields and between packing houses and the Rotterdam sea port are considerable. However, the GHG emissions from transportation do not make a large contribution to the CF of yellow melon in any of the scenarios. The transport of materials to farms accounts for 8 percent of GHG emissions when the transport of all inputs is done by truck (scenario 3 in Fig. 5) or when emissions from on-farm and packing processes are reduced (scenario 5). The contribution of melon transportation from Brazil to Europe ranged from 9 percent when processes in the Low Jaguaribe and Açu region emitted higher amounts of GHG (reference situation, scenarios 1 and 4) to 16 percent when lower emissions came from these processes (scenario 5).

Uncertainty regarding CF values mainly concerns variations in carbon fractions of vegetation types and soil, in GHG emission factors, and in transport distances (Fig. 4). The carbon fraction of Savanna was estimated by MCT (2010b) and varied according to local physiognomies. The soil carbon content varies according to soil types that may be found in the studied region (low clay activity, high clay activity, and sandy soils). Emission factors used to

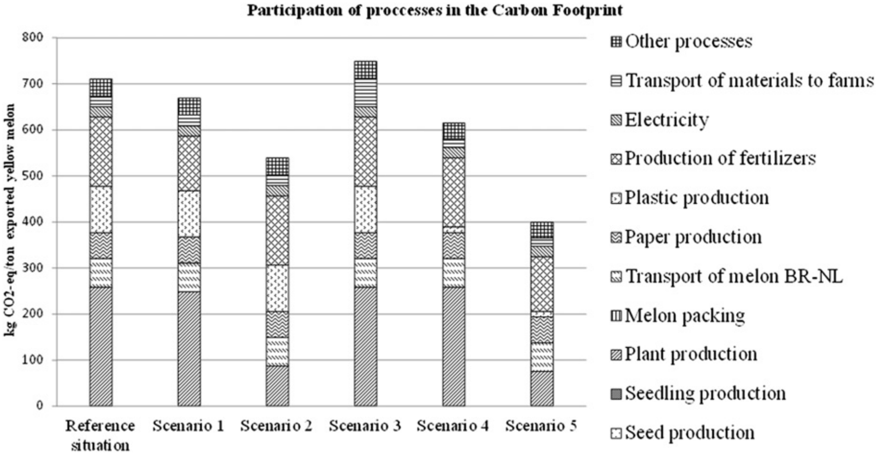

Fig. 5. Yellow melon CFs in different scenarios, considering the participation of each process.

estimate GHG emissions (IPCC, 2006; MCT, 2010a) may be two times more or less than the average value (for example, factors for nitrous oxide). Distances from sites where materials and fuels are produced to melon farms and packing houses may also vary from farm to farm. The estimation of these distances when considering major exporting countries and national states is an approximation of the real distances.

Furthermore, uncertainty may be higher in scenario 3, when all inputs used in farms and packing houses are nationally produced. GHG emissions from the production of these inputs are probably different from the ones presented in the ecoinvent database. Since no national inventory database is available, the GHG emissions from these production processes were taken from ecoinvent to all scenarios.

4.4. Comparison with other studies

The CF result of 710 kg CO_2-eq/t of exported yellow melon from the Açu Jaguaribe region in the reference scenario is low compared to results reported in earlier studies (Cellura et al., 2012; Audsley et al., 2009). The average CF of Italian melon cultivated in greenhouses in southern Sicilia was 1427 kg CO_2-eq/t melon (Cellura et al., 2012), the CF of melons cultivated in Europe was 1550 kg CO_2-eq/t, and of melons produced outside Europe, 1740 kg CO_2-eq/t (Audsley et al., 2009).

Differences between these studies may result from differences in the production system (for example, production in open fields versus greenhouses, amount of plants per area, and amounts of agrochemicals applied), as well as from methodological approaches used in the estimation of GHG emissions (for example, consideration of emissions from land transformation and method for estimating GHG emissions). The Italian melon production system used greenhouses and higher amounts of total fertilizers, pesticides, and diesel than this study, which may have been the main factor contributing to the higher CF (Cellura et al., 2012). The Italian melon study estimated GHG emissions from the production of inputs, but did not account those from land use change and seed production. The method used to calculate nitrogen emissions was also different from this study (Brentrup et al., 2000; EPA, 1995).

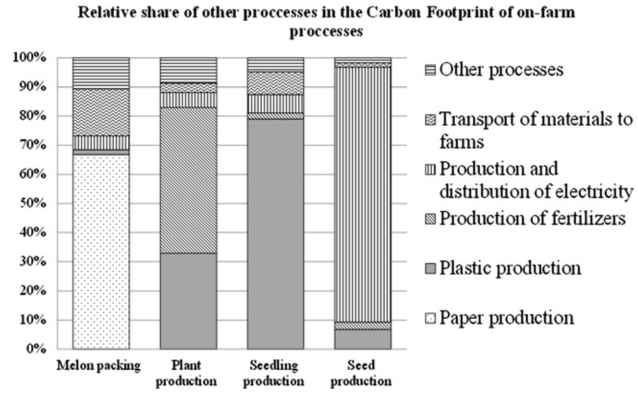

Fig. 6. Relative share of processes in the overall CFs of melon-related processes (reference situation).

Audsley et al. (2009) calculated the CF for major products consumed in England using IPCC GWPs (IPCC, 2007) and proxy data to the calculations regarding emissions from melon production. The broader scope of this study, including emissions from distribution and final consumption, may explain in part the higher CF values related to melon production.

Other factors that shall be considered include the unknown melon variety studied by Cellura et al. (2012) and Audsley et al. (2009). Some melon varieties require higher amounts of agrochemicals than others. According to the interviewed farmers, the yellow melon demands less fertilizer, for example, than cantaloupe and honeydew.

5. Conclusion

The CF for Brazilian yellow melon in the reference situation is 710 kg CO_2-eq/t of exported melon (ranging from 632 to 787 kg CO_2-eq/t melon). Emissions from upstream and downstream processes have a large share in this total CF. Emissions from seedling, plant production, and melon packing contribute less than 50 percent in all scenarios, including the reference situation. Plant production is the main process responsible for GHG emissions among all processes in the Low Jaguaribe and Açu region.

Scenario analysis shows that the CF can be reduced to 399 kg CO_2-eq/t of exported melon. This reduction is achievable when melons are produced on farms located in previously existing agricultural areas, the nitrogen fertilization is reduced from 6 to 4 kg N/t melon, materials are transported by ship to the farms, and plastic field trays are not used in melon fields.

This study is the first to quantify the CF for Brazilian melons. A considerable amount of high quality primary data was collected about the melon farming process. However, our GHG estimates from these processes are based on generic emission factors, and not on farm-specific factors. For instance, GHG emissions from seed, seedling, plant production, and melon packing are estimated using emission factors defined by IPCC (2007) and indicated by certification standards, such as PAS 2050 and The Product Life Cycle Accounting and Reporting Standard. However, each farm is unique in terms of soil quality, amount of precipitation, and other parameters. Also, production systems may vary from farm to farm. Thus, field measurements or estimations of GHG emissions in a specific farm context may further improve our results and reduce the uncertainty regarding some emission factors. Nevertheless, we consider the results of this study robust as a first assessment of CFs of melons produced in Brazil. This study may serve as an example for similar studies in other countries or of other crops.

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Appendix A. Procedures used to estimate GHG emissions

1. CO_2 emissions from land use change (from forest to agriculture)

1.1. Biomass change (MCT, 2010b)

$$E = \frac{(A*(C - \text{avAgri}))}{20} * \frac{44}{12}$$

where E = Carbon emission (t CO_2.year^{-1}.kg melon, seed, or seedling^{-1}), considering a period of 20 years from land conversion; A = area converted (ha year^{-1} kg melon, seed, or seedling^{-1}); C = carbon stock in biomass and dead organic matter (t C/ha); avAgri = Carbon stock in the crop area (t C/ha).

According to the Brazilian GHG National Inventory (MCT, 2010b), the values of C for the Caatinga Biome physiognomies that mostly occur in the studied region are 14.9 tC/ha (savannah steppe – Ta and Tp) and 24.1 tC/ha (savannah park – Sp). The value for avAgri is estimated in 1.28 tC/ha for melon crop. This estimation was based on the measurement of dry matter and total carbon content of five melon plants at harvest.

CO_2 emissions from biomass carbon change were calculated to each Caatinga Biome physiognomy, and the average of the results was used. The emissions were accounted for yearly after land transformation and considered a distributing time of 20 years (IPCC, 2007; WRI and WBCSD, 2011).

1.2. Soil carbon change (MCT, 2010b)

$$\text{Es} = \left(A*\text{Csoil}*\frac{\left[\text{fc}(t_0) - \text{fc}\left(t_f\right)\right]}{20} * \frac{44}{12} \right)$$

$$\text{fc}(t) = f_{LU}*f_{MG}*f_I$$

where Es = Liquid emission of carbon from soil (t CO_2.year^{-1}.kg melon, seed, or seedling^{-1}); A = area (ha year^{-1} kg melon, seed, or seedling^{-1}); Csoil = Carbon stock in soil on the association soil-vegetation in the area (tC/ha); fc(t) = factor of carbon alteration in the time t (dimensionless); f_{LU} = factor of carbon alteration related to land use (dimensionless); f_{MG} = factor of carbon alteration related to management regime (dimensionless); f_I = factor of carbon alteration related to input of organic matter (dimensionless).

According to the Brazilian GHG National Inventory (MCT, 2010b), the value of Csoil varies in the studies region and can be: 2.42 kg C/m^2 in soil with high clay activity, 2.58 kg C/m2 in soil with low clay activity (Ferralsol), 2.62 kg C/m^2 in soil with low clay activity (no Ferralsol), and 1.51 kg C/m^2 in Arenosols. CO_2 emissions from soil carbon change were calculated to each soil type, and the average of the results was used.

The factors f_{LU}, f_{MG}, $f_{I,}$ and fc to agricultural areas are 0.58, 1.16, 0.91, and 0.612, respectively. In forested areas, fc is 1.

1.3. CO_2 emissions from land use change (from agriculture to agriculture)

According to MCT (2010b), no changes in biomass and soil carbon occur when agricultural land from a crop is used to plant other crop.

2. CO_2 emissions from the use of urea as fertilizer (IPCC, 2006)

$$CO_2 - \text{C Emission} = (M*\text{EF})*\frac{44}{12}$$

where CO_2–C Emission = CO_2 emissions from urea application (t CO_2 year^{-1} kg melon, seed, or seedling^{-1}); M = amount of urea (t year^{-1} kg melon, seed, or seedling^{-1}); EF = emission factor, that is 0.20.

3. CO_2, CH_4 and N_2O from fuel burning (off road transportation) (IPCC, 2006)

$$\text{Emission}_i = \text{Volume}*\text{density}*\text{NCV}*\text{EF}_i$$

where Emission = emission of CO_2 (kg.year^{-1} kg melon, seed, or seedling^{-1}); i = GHG (CO_2, CH_4 e N_2O); Volume = fuel volume (L year^{-1} kg melon, seed, or seedling^{-1}); Density = fuel density (kg/L); NCV = Net calorie value (TJ/kg); EF$_i$ = Emission factor for GHG i.

According to the Brazilian Energy Balance (MME, 2011):

- The density of Brazilian diesel is 0.84 kg/l;
- The NCV is 10,100 kcal/kg (1 kcal = 0000000041868 TJ). NCV is 0.00004228668 TJ/kg.

According to IPCC (2006), the EF for diesel used in agriculture is:

- 74,100 kg/TJ for CO_2;
- 4.15 kg/TJ for CH_4;
- 28.6 kg/TJ for N_2O.

4. CH_4 and N_2O emissions from biomass burning (IPCC, 2006)

$$CH_4 - \text{Emissions} = A*M_b*C_f*G_{ef}$$

where CH_4-Emissions = methane emissions in the year (kg CH_4 year^{-1} kg melon, seed, or seedling^{-1}); A = area burnt, (ha year^{-1} kg melon, seed, or seedling-1); M_b = mass of fuel available for combustion (kg ha^{-1}); C_f = combustion factor, dimensionless; G_{ef} = emission factor, g kg^{-1} dry matter burnt.

According to IPCC (2006), "$M_b \cdot C_f$" to Caatinga (savanna) is 0.21. The G_{ef} value for CH_4 is 2.3 and for N_2O, 0.21.

5. Emissions of N_2O from fertilizers and crop residues use (IPCC, 2006)

5.1. Direct emissions

$$N_2O - N - \text{inputs} = ((F_{SN} + F_{ON} + F_{CR} + F_{SOM})^*\text{EF1})\ ^*\frac{44}{28}$$

where N_2O–N-inputs = soil N_2O emissions (kg N_2O year^{-1} kg melon, seed, or seedling^{-1}); F_{SN} = amount of synthetic N fertilizer applied (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{ON} = amount of compost N fertilizer (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{CR} = amount of N in crop residues (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{SOM} = amount of N mineralized because of land use changes (kg N year^{-1} kg melon, seed, or seedling^{-1}); EF1 = emission factor $(\text{kg N})^{-1}$.

According to IPCC (2007), EF1 is 0.01.

$$F_{CR} = \left(\text{crop}^*\left(\text{Area} - \text{Area}_{\text{burnt}}\right)^*C_f{}^*\text{Frac}_{\text{renew}}\right)^*[(R_{AG}{}^*N_{AG}\ ^*(1 - \text{Frac}_{\text{remove}})) + (R_{BG}{}^*N_{BG})]$$

where Crop = harvested dry matter (kg d m year^{-1} ha^{-1}); Area = harvested area (ha year^{-1} kg melon, seed, or seedling^{-1}); $\text{Area}_{\text{burnt}}$ = area burnt (ha year^{-1} kg melon, seed, or seedling^{-1}). In the melon case, it is zero; C_f = Combustion factor. Not used in the melon case; $\text{Frac}_{\text{renew}}$ = fraction of total area that is annually renewed. For melon, it is 1; R_{AG} = ratio between above-ground dry matter of residues (kg d m) and harvested yield (kg d m); N_{AG} = N content of above ground residues (kg N/kg d m); $\text{Frac}_{\text{remove}}$ = fraction of above ground residue that was removed from the area. In the case of melon, it is zero; R_{GB} = ratio between below ground residues (kg d m) and crop harvested yield (kg d m); N_{GB} = N content of below ground residues (kg N/kg d m).

$$F_{SOM} = \left[\left(\Delta C_{\text{soil}}{}^*\frac{1}{R}\right)^*1000\right]$$

$$\Delta C_{\text{soil}} = \left(A^*\text{Csoil}^*\frac{\left[\text{fc}(t_0) - \text{fc}\left(t_f\right)\right]}{20}\right)$$

$$\text{fc}(t) = f_{LU}{}^*f_{MG}{}^*f_I$$

where F_{SOM} = amount of N mineralized in soil because of change in land use (kg N year^{-1} kg melon, seed, or seedling^{-1}); ΔC_{soil} = amount of C lost by land use change (t C); A = area submitted to land use change (Forest to Agriculture, see item 1.2) (ha year^{-1} kg melon, seed, or seedling^{-1}); Csoil = carbon in soil before land use change (see item 1.2) (t C/ha); $f_c = \text{fc}(t)$ = factor of carbon alteration in the time t (dimensionless); f_{LU} = factor of carbon alteration related to land use (dimensionless); f_{MG} = factor of carbon alteration related to management regime (dimensionless); f_I = factor of carbon alteration related to input of organic matter (dimensionless). R = C:N ratio of the soil organic matter. According to IPCC (2006), it is 15 in land use change from forest to cropland.

5.2. Emissions from volatilization of NH_3 and NO_x

$$N_2O_{ATD} - N = \{[(F_{SN}{}^*\text{FRAC}_{\text{GASF}}) + ((F_{ON} + F_{PRP})^*\text{Frac}_{\text{GASM}}) \times]^*\text{EF}_4\}\ ^*\frac{44}{28}$$

where N_2O_{ATD}–N = amount of N_2O produced from atmospheric deposition of N volatilized from managed soil (kg N_2O year^{-1} kg melon, seed, or seedling^{-1}); F_{SN} = amount of synthetic N fertilizer applied (kg N year^{-1} kg melon, seed, or seedling^{-1}); $\text{FRAC}_{\text{GASF}}$ = fraction of N synthetic fertilizer that volatilizes as NH_3 and NO_x. It is 0.10; F_{ON} = amount of compost N fertilizer (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{PRP} = N amount of urine and dung deposited by animals on pasture, range, or paddock (kg N year^{-1} kg melon, seed, or seedling^{-1}). No amount used in melon production; $\text{FRAC}_{\text{GASM}}$ = fraction of N organic fertilizer that volatilizes as NH_3 and NOx. It is 0.20; EF_4 = Emission factor. It is 0.01.

5.3. Emissions from leaching and run off

Although drip irrigation is used in melon farms, during the rainy season, the difference between the amount of rain and the potential evaporation in the area is higher than the soil water holding capacity that is poor in sandy soils. So the calculation of indirect N_2O emissions from leachate (mainly) and run off was performed. According to IPCC (2006):

$$N_2O - N = \left((F_{SN} + F_{ON} + F_{CR} + F_{SOM})^*\text{Frac}_{\text{Leach}-(H)}{}^*\text{EF}_s\right)\ ^*\frac{44}{28}$$

whereas N_2O–N = amount of N_2O produced from leaching and runoff of N additions to soils (kg of N_2O year^{-1} kg melon, seed, or seedling^{-1}); F_{SN} = amount of synthetic N fertilizer applied (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{ON} = amount of compost N fertilizer (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{CR} = amount of N in crop residues (kg N year^{-1} kg melon, seed, or seedling^{-1}); F_{SOM} = amount of N mineralized because of land use changes (kg N year^{-1} kg melon, seed, or seedling^{-1}); $\text{FRAC}_{\text{Leach-(H)}}$ = fraction of all N added to/mineralized that is lost through leaching and run off. It is 0.30; EF_5 = emission factor $(\text{kg N})^{-1}$. According to IPCC (2006), EF is 0.0075.

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