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REGIONAL TOPICS FROM LATIN AMERICA

An agile approach for evaluating the environmental-economic performance of cropping systems at experimental stage: the case of Brazilian mango

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Abstract

Purpose The lack of approaches to consider the economic-life cycle environmental performance of cropping systems at experimental stage and the absence of evaluations regarding alternative mango systems are issues addressed in this paper. In this study, an approach for assessing the environmental-economic performance of alternative crop systems, at the experimental stage, is proposed and applied to the mango experiment in Brazil. This approach may be used in other assessments of cropping systems at experimental stage.

Methods The proposed approach encompasses three consecutive evaluations: agronomic and environmental-economic. Initially, the agronomic evaluation statistically compares the yield of alternative cropping systems (treatments in the experiment). Next, a treatment is selected among those with significant better yield and compared to the treatment representing the conventional system, considering environmental and economic criteria. The environmental criteria are the carbon and water footprints of the selected treatments, according to ISO 14067 and 14,046, while the economic is profitability (revenue minus costs with labor and inputs). This approach was applied to evaluate an 8-year mango experiment in the Sao Francisco Valley, Brazil, which intercropped mango trees with two types of plant mixtures (cover crops with different plant mixes), applying two soil management systems (tillage and no-tillage).

Results and discussion The agronomic assessment that statistically compared yields showed that four treatments (T1, T2, T4, and T5) obtained higher yields than those representing the conventional system (T3 and T6). Treatment T4 was selected among the ones with higher yields, and compared with T6 (conventional system), considering the economic and environmental criteria. The economic analysis showed that in 30 years (expected orchard life time), T4 generates a profit that is 44% higher than T6. Regarding the environmental analysis, T4 presents a 16% lower carbon footprint and from 16 to 435% lower water footprint than T6, according to the impact category considered. The scenario where land use changed from an annual crop (melon) to mango orchard further reduced both carbon and water footprints of mangoes produced in T4.

Conclusions The application of the proposed approach to the mango experiment resulted in the reduction of time and data requirements when evaluating the economic-environmental performance of mango alternative cropping systems, allowing the selection of best performing treatment. The assessment of economic-environmental performance showed that treatments with plant mixtures used as cover crops between lines of mango trees, independently of the type of mix used or the soil management applied, enhance the overall performance of mango production.

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1 Introduction

Many approaches to assess the sustainability of cropping systems have been proposed. These commonly combine indicators related to one or more aspects (social, economic, and environmental) of sustainability (Deytieux et al. 2016). Most of these approaches did not consider social aspects and relied on the profitability of the system to evaluate the economic performance and on a set of environmental aspects, related to soil and water, to evaluate the environmental performance.

Furthermore, consideration of the potential life cycle impacts of cropping systems and their integration with economic analysis has rarely been included in evaluations of experimental cropping systems. A few prior studies have performed economic and life cycle–based environmental assessments: (i) Nemecek et al. (2011a, b) compared the environmental performance of organic, conventional, intensive, and extensive farming systems for arable crops, using a financial functional unit and data from two different experiments in Switzerland; (ii) Santos et al. (2018) compared three rotation systems in terms of yield, economic, and environmental performance per kilogram of melon, using data from one experiment in the Sao Francisco Valley, Brazil; and (iii) Falcone et al. (2019) compared the economic and environmental performance of four wheat production systems, using a financial functional unit and data from an experimental area in southern Italy. In these studies, the common approach was to evaluate all treatments, a strategy that was very time consuming and data intensive.

Regarding mango production, previous studies evaluated the environmental performance of conventional mango production in Brazil (Carneiro et al. 2019; Basset-Mens et al. 2016), Mexico (NMB 2010), Taiwan (Nicki 2016), and Australia (Ridoutt et al. 2010), at commercial scale, not focusing on alternative systems at experimental stage. The combined economic-environmental assessment of mango cropping systems was not performed so far, at experimental or commercial scales. However, this crop is well adapted to tropical dry climate and of special interest for producing countries in Asia, Australia, and Latin America as well as importing countries in all continents.

Native to South Asia, the mango tree (*Mangifera indica* L.) is a fruit tree species of the family Anacardiaceae. It is among the trees introduced to Brazil that has adapted well, when irrigated, to the edaphoclimatic conditions of the Brazilian semi-arid region (Silva and Gomes 2004).

The Sao Francisco Valley, located in the Brazilian semi-arid region, is the largest mango-producing and exporting site in Brazil. According to data from the Brazilian Institute of Geography and Statistics (IBGE 2020), in 2018, the area designated for mango cultivation in the Valley was approximately 36,000 ha, with an average yield of 24 t/ha. In that year, approximately 148,000 t of mangoes, produced in the valley, were exported, mainly to Europe (71%) and the USA (19%) (MAPA 2020).

In this region, mango production is intensive and monocultural (Carneiro et al. 2019). Intensive systems are characterized by a high utilization of inputs external to the agricultural area, including water for irrigation and synthetic fertilizers, as well as frequent soil movement (Willekens et al. 2014). The use of synthetic fertilizers and irrigation water in crop production may contribute to climate change, soil degradation, and increased water scarcity, already a feature of semi-arid regions (Smith et al. 2015a, b).

The evaluation of carbon and water footprints of conventional mango production in Brazil, performed by Carneiro et al. (2019), proposed the intercropping of mangoes with cover crops to reduce mango footprints. Cover crops are additional crops to a cash crop, applied in crop rotations and intercropping systems. Cover crops are usually introduced in agriculture systems to improve soil cover, to increase fertility through green manure, and/or to increase revenues if the cover crop is harvested. The use of cover crops has been considered a promising agriculture practice by farmers dealing with soil degradation in Europe and China (Barão et al. 2019). The use of cover crops in semi-arid regions may increase below ground biomass, carbon, and nitrogen soil storage; provide soil coverage; and improve water retention in the soil (Giongo et al. 2016; Pereira Filho et al. 2016).

In order to evaluate alternative agricultural systems to the mango monoculture, a long-term experiment was commenced in 2009 at the Bebedouro experimental station, in the Sao Francisco region, Northeast, Brazil. This focused on intercropping mango trees with plant mixtures as cover crops. Three types of cover crops and two types of soil management were investigated in this experiment. The effects of cover crops and soil management on nutrient cycling and mango yield were reported, for the first 6 years of this experiment, by Brandão et al. (2017a, b). A broader assessment of the experiment is missing but necessary to support decisions about which treatment to select considering its overall economic-environmental performance.

In this study, an approach for assessing the environmental-economic performance of alternative crop systems, at the experimental stage, is proposed and applied to the mango experiment 2009 at the Bebedouro experimental station. The objective was to identify which treatment performed better, applying the proposed approach, and to indicate it for future use by mango producers in the Sao Francisco Valley. The proposed approach may be used in other assessments of cropping systems at experimental stage over the world.

2 Material and methods

2.1 Description of the long-term experiment

Data was collected at the Bebedouro Experimental Station of Embrapa Semi-arid, in Petrolina, Pernambuco (latitude 09°09′ S, longitude 40°22′W, and altitude 365.5 m), between 2009 and 2017. In the experimental area (1 ha), mango trees were intercropped with a plant mix chosen to provide green manure and carbon storage between the lines of trees.

The soil type of this site is ultisol dystrophic plinthic, loamy/clayey plain relief. The climate of the region, according to the climatic classification of Köppen, is type BSwh'; semi-arid, with an average annual rainfall of 567 mm and the rainy period between January and April. The average air temperature ranges from 24 to 28 °C (Brandão et al. 2017a).

The experiment was laid out in a split-plot design, with two plots and three subplots (Table 1). In the plots (1080 m^2 each), two soil management systems were evaluated: with and without tillage. In the subplots (360 m^2 each), cover crops, annually sown between the lines of mango trees, were evaluated.

The following combinations of plants were used as cover crops, in two subplots: (i) 25% leguminous plants and 75% grasses and oilseeds (non-leguminous) and (ii) 75% leguminous and 25% grasses and oilseeds. In the third subplot, spontaneous vegetation grew naturally, without human intervention, representing typical conditions in the traditional mango farms of the Sao Francisco Valley.

In each subplot, nine mango seedlings of the Kent variety were transplanted in September 2009. Plant mixtures were annually sown in December, since 2009, and cut 70 days after sowing, without grain harvest, with the aim of increasing the amount of nutrients in the soil as well as improving the soil structure.

The following leguminous, grass, and oilseed species that composed the plant mixtures were selected because of their high adaptability to semi-arid conditions (Gomes et al. 2004; Faria et al. 2004; Faria et al. 2007; Giongo et al. 2016): (i) legumes: calopo (*Calopogonium mucunoide Desv.*), velvet bean (*Stizolobium aterrimum L.*), gray-seeded mucuna (*Stizolobium cinereum Piper & Tracy*), crotalaria (*Crotalaria juncea L.*), rattlebox (*Crotalaria spectabilis Roth*), jack beans (*Canavalia ensiformis* (*L.*) *DC*), and lab-lab bean (*Dolichos lablab L.*); (ii) grasses: sesame (*Sesamum indicum L.*), corn (*Zea mays L.*), pearl millet (*Pennisetum americanum* (*L.*) *Leeke*), and milo (*Sorghum vulgare Pers.*); and (iii) oilseeds: pigeon pea (*Cajanus cajan L.*), sunflower (*Helianthus annuus L.*), and castor oil plant (*Ricinus communis L.*). The species that predominated in the spontaneous vegetation were Benghal dayflower (*Commelina benghalensis L.*), purple bush bean (*Macroptilium atropurpureum* (*DC*) *Urban*), Florida beggarweed (*Desmodium tortuosum* (*Sw.*) *DC*), and goat's head (*Acanthospermun hispidum DC*).

In the plot with tillage of the cover crop phytomass, harrowing and furrow opening were used for sowing the seeds of the plant mixtures, and, at the end of the cycle of cultivation, plowing followed by harrowing of the phytomass were carried out. In the treatment with spontaneous vegetation, only plowing and harrowing were carried out.

In the no-tillage plot, sowing of the plant mixtures was carried out by furrow opening. At the end of the crop cycle, the phytomass of the plant mixtures and any spontaneous vegetation was cut close to the soil and deposited on its surface, using an off-set rotary shredder.

Two types of irrigation systems were used in all treatments: one involving micro sprinklers in the mango tree lines and the other used dripping between the lines, in the area with plant mixtures or spontaneous vegetation. Irrigation management was carried out by monitoring the soil water potential and the water demand at various stages of the cropping, as described by Brandão et al. (2017a).

Fertilizers were applied via fertigation to the mango trees. No fertilizer was applied to cover crops, only water for supplementary irrigation of plant mixtures, with the same volume being applied to all treatments.

Before manual mango harvesting, the fruits were checked for appearance, maturation, and coloration.

Table 1 Treatments evaluated in the experimental area

Treatment	Subplot (cover crops)	Plot (soil management)
T1	Plant mix 1: 75% leguminous + 25% non-leguminous	No tillage
T2	Plant mix 2: 25% leguminous + 75% non-leguminous	No tillage
T3	Spontaneous Vegetation	No tillage
T4	Plant mix 1: 75% leguminous + 25% non-leguminous	Tillage
T5	Plant mix 2: 25% leguminous + 75% non-leguminous	Tillage
T6	Spontaneous Vegetation	Tillage

After harvest pruning, and only in the last year of the experiment, paclobutrazol (PBZ) was applied. This product is a growth regulator that inhibits vegetative growth, allowing floral induction and mango production at any time of the year (Chatzivagiannis et al. 2014). Application of this product began in 2017 because of the low mango yield occurring under all treatments (average of 41 kg/plant between 2015 and 2016 at the experimental station) compared to the commercial orchards using PBZ (annual production of up to 106 kg/plant, according to Carneiro et al. 2019).

2.2 Approach for assessing the economic-environmental performance of cropping systems

The agile approach proposed in this work and applied to the mango experiment has three steps covering agronomic, economic, and environmental performance (Fig. 1). Initially, the agronomic performance is evaluated (Table 1) to identify the treatments that present the best and worst results in terms of yield alone. Sequentially, the economic and environmental performance evaluations are performed.

In this approach, a system offering better yield and better environmental and economic performance is seen as more sustainable than conventional practice. A system with high yield may require high (costly) inputs and services, resulting in lower profits. Furthermore, it may release highly contaminating pollutants or consume excessive resources increasing environmental impacts. Thus, analysis is undertaken of both economic and environmental performances, as is necessary and complementary to the raw agronomic performance.

2.2.1 STEP 1: assessment of agronomic performance

The agronomic performance was assessed by statistical analysis of yield of each treatment. The productive capacity of agricultural systems, measured by the yield, has been the most commonly applied indicator for assessing the technical performance of the cropping systems (Deytieux et al. 2016).

The statistical analysis of yield allows the selection of a treatment that is in the group of those with higher and significantly different yield. If the yield of all treatments in an experiment, encompassing alternative and conventional, do not differ from each other, conventional and alternative treatments are alike. In this situation, if previous works already assessed the environmental-economic performance of conventional system, no further work is necessary.

The data for mango yield (from the harvest years 2015 to 2017) in the Brazilian experiment were tested for normality, Shapiro-Wilk's test, and for homoscedasticity (equal variance), Bartlett's test for analysis of variance (ANOVA). Data homogeneity (Lewis 1995) made it appropriate to use a triple factorial analysis considering the soil management (tillage and no tillage), cover crops (plant mixes and spontaneous vegetation), and time (2015, 2016, and 2017). Two hypotheses were considered: (i) H0 (null): the factors do not significantly alter the mango tree yield and (ii) H1: the factors significantly alter the mango tree yield. If the P value > 0.05, H0 was accepted. Tukey's test was performed for factors with P value < 0.05. Analysis was performed using the software Statistica by STATSOFT (2007) and R (R Core Team 2015).

The treatment presenting the best yield was compared, economically and environmentally, to that representing the conventional system. If two or more treatments produce better yields, just one of them is chosen, since there is no significant difference among them.

2.2.2 Assessment of economic performance

Profitability is the most used indicator applied for assessing the economic performance of cropping systems (Deytieux et al. 2016) and was selected for this study. Data was collected to estimate the total annual cost, resulting from the purchase of inputs and services for agricultural purposes, and the gross revenue from the commercialization of mangoes in the external market. Profitability was determined by subtracting total annual cost from total revenue.

The prices of inputs and services (manual and mechanized activities performed in the orchard from its establishment until year 8) were estimated in 2017 market prices, provided by the input sellers in Petrolina city and by the manager of the Experimental Station (regarding agriculture services). It is important to note that the market prices for inputs at commercial farms may be lower because they get advantage from buying high quantities of inputs at a time, reducing input prices. In the calculation of gross revenue, the average price of mangoes in the international market (US$0.46/kg of mango), for the years 2015, 2016, and 2017, was applied.

Considering that mango orchards are productive for 30 years, the economic analysis was performed for this period, in order to indicate when profit starts, and the total profit obtained, in the compared treatments over the whole orchard life cycle. In predicting costs and revenues from year 9 onwards, the same yield, mango price, and costs used to evaluate year 8 were applied in the following years.

2.2.3 STEP 3: assessment of environmental performance

The environmental assessment was based on estimation of product carbon and water footprints following ISO 14067 (ISO 2013) and ISO 14046 (ISO 2014), respectively. Both carbon and water footprint determinations applied the life cycle assessment (LCA) method, the phases of which are presented in ISO 14040 (ISO 2006a) and ISO 14044 (2006b).

The system presenting better results for both carbon and water footprints was regarded as having the best environmental performance. According to Tait et al. (2015), carbon

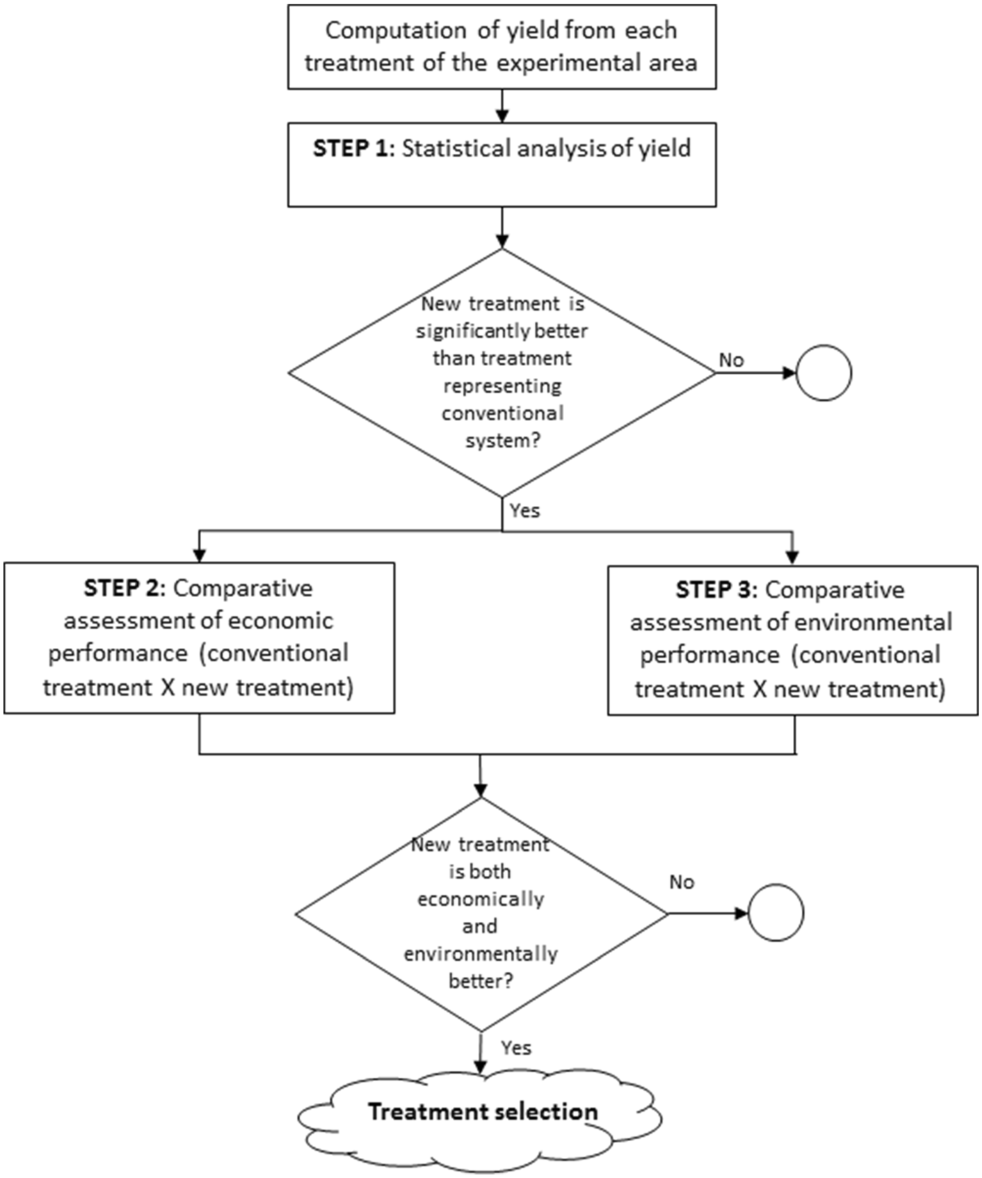

Fig. 1 Proposed approach for evaluating the environmental-economic performance of the experimental cultivation systemst

emissions are one of the major worries of Japanese and European fruit consumers and they are willing to pay more for fruits presenting a lower carbon footprint. In addition, the water footprint of products is important for food products since water shortages and pollution are expected to increase with population growth and increases in temperature, especially in semi-arid regions (FAO 2009).

It is noteworthy to mention that there is a PCR for fruits and nuts (EPD International AB 2019), updated in 2019 that can be used by mango producers interested in environmental certification by ISO 14025. This PCR covers other impact categories than those covered by the water and carbon footprints and requires cradle-to-grave scope. In this way, the approach proposed in this study does not follow this PCR.

The next subsections describe the decisions made in each LCA phase (objective and scope, inventory, impact assessment and interpretation) for the mango experiment.

Objective and scope The aim of the life cycle assessment was to compare treatments representing alternative and conventional systems. This study was from cradle-to-farm gate, covering the processes of production and transportation of inputs, land use change, seedling, and crop production (Fig. 2). Data was collected about the following activities within the crop production: soil preparation, planting of mango seedlings, sowing of plant mix, cropping, irrigation, fertilization, phytosanitary control, application of growth regulator, and harvesting.

The functional unit adopted was 1 kg of harvested mango with export quality. In this quality pattern, mango fruits were manually harvested in stage 2 of maturity (peel color green reddish) and selected when fresh-looking, intact, firm, and healthy (Filgueiras et al. 2000). Fruits affected by decay, holes, or illness were discarded.

Inventory Primary data was gathered into a crop production inventory: yield, energy, water, and agrochemicals. This inventory covered the first 8 years of the orchard (2009 to 2017), with harvesting from year 6 to 8. The arithmetic means of the masses of inputs and outputs, over 8 years of orchard life, were calculated for the inventory as representing an average year. Data was collected using questionnaires to the researchers responsible for the experiment and to managers of the Experimental Unit.

Emissions of pollutants from land use change and agricultural production were accounted as follows: (i) emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), according to IPCC (2006); (ii) emissions of ammonia (NH_3) and nitrogen oxides (NO_x) into air, of phosphorus (P), phosphate (PO_4^{-3}), and nitrate (NO_3^-) into water, and of heavy metals and pesticide residues into soil, according to Nemecek et al. (2015). The equations and emission factors applied in the calculation of these emissions are described in Annex A in the supplementary material.

For estimation of greenhouse gases (GHGs) resulting from land use change, the worst scenario was assumed to have occurred, i.e., 100% *Caatinga* vegetation (type of Savanna) having been converted into agricultural use (mango production) less than 20 years ago. An alternative scenario is considered in Section Interpretation of footprint results. To support these calculations, samples of soil, cover crops, and mango trees were collected from each plot to quantify the carbon and nitrogen contents in the phytomass, mango trees, and soil. The carbon and nitrogen content present in *Caatinga* soil and vegetation was obtained from MCTI (2010).

Composite soil samples were collected annually from between the mango trees from the 0–5-cm, 5–10-cm, 10–20-cm, and 20–40-cm layers. With regard to phytomass, three samples of the above soil plant were collected, after cutting, in each subplot in 1-m^2 squares randomly placed on the lines of cover crops. Three composite samples, containing approximately 1 kg of fresh phytomass (roots, trunk, stem, and leaves), from three mango trees were collected at the stabilized production stage.

The dry and wet matter of each sample was then determined. The amount of carbon and nitrogen present in the phytomass and in the soil was determined by dry combustion in the elemental analyzer LECO, model CHN 600 (Matejovic 1997).

The inventory of inputs, outputs, and emissions arising from land use change and crop production is presented in the supplementary material (Table B1, Annex B).

Secondary data was used to inventory the processes related to the production of agricultural inputs (except for mango

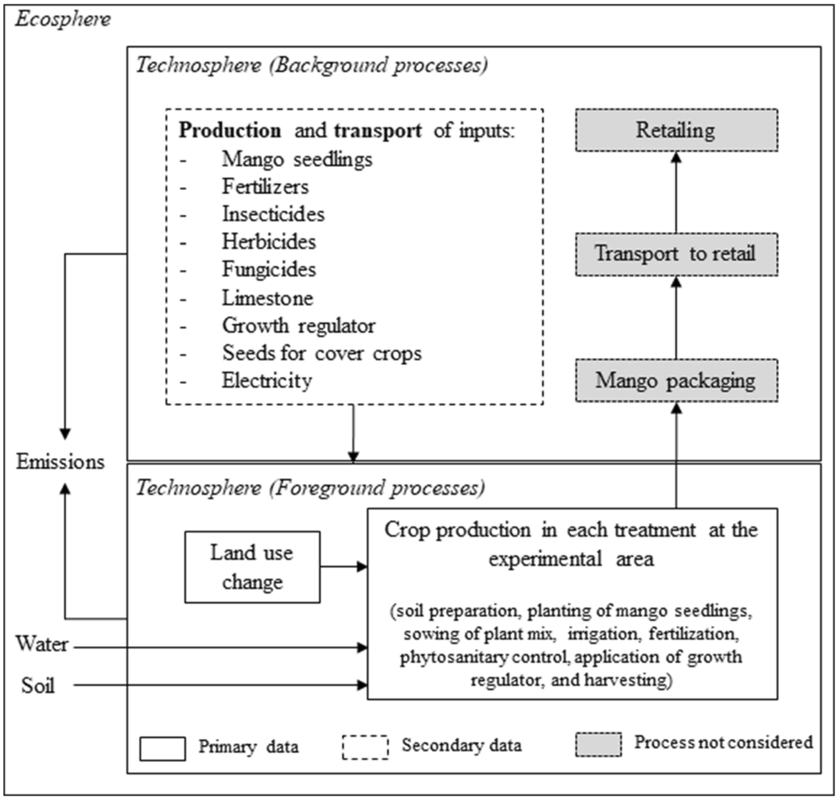

Fig. 2 Product system in the environmental-economic evaluation of alternative mango cropping systemsr

seedlings and seeds of the plant mixtures), their transportation to the mango orchard, and the agricultural mechanized operations carried out in the orchard (plowing, harrowing, mowing, and application of fertilizers and pesticides). This data was obtained from the ecoinvent database v. 3.3. Table B2 (Annex B in the supplementary material) shows the relation between input name and ecoinvent inventory name. The data regarding mango seedling production was based on Carneiro et al. (2019). For the seeds, data for two species were included: pigeon pea (*Canajus Cajan*) from the leguminous group, following Souza Filho et al. (2007), and maize (*Zea mays*) from the non-leguminous, following Valentini et al. (2009).

Carbon and water footprint analysis The carbon footprint was determined using the ILCD midpoint method (JRC and IES 2011), which considers the global warming potential of GHGs over a 100-year period, according to the IPCC (2013). The carbon footprint is measured in kg CO_2-Eq.

The water footprint considered the following impact categories: marine eutrophication (kg N Eq), freshwater eutrophication (kg P Eq), human toxicity (cancer and non-cancer, measured in CTUh), aquatic ecotoxicity (CTUe), and water scarcity (m^3 Eq). Except for water scarcity, the other categories were evaluated by the ILCD midpoint method (JRC and IES 2011). Water scarcity was evaluated by the AWARE method (Boulay et al. 2018) with characterization factors at country level available in the LCA software Simapro 9.0.0.35.

Interpretation of footprint results The carbon and water footprints of the two selected treatments were compared while also considering possible alternative scenarios for crop production and the uncertainty of results.

Scenario analysis was applied to the treatment that presented the best overall environmental performance, considering both carbon and water footprints. The aim was to evaluate the environmental consequences of possible changes in the mango production processes. Thus, the footprints of the defined scenarios were compared to those of the "best" reference cropping system.

In the reference situation, the 8-year-old mango orchard was considered to have been planted in an area previously occupied by native vegetation (*Caatinga*) (see Sect. 2.2.3.1) and to use a growth regulator only in the eighth year (Sect. 2.1). However, orchards may be developed in areas previously occupied by an annual crop, resulting in greater carbon stock in biomass and soil. Furthermore, the growth regulator can be applied annually to increase the yield per tree, from the sixth year (when harvesting starts) onwards (Chatzivagiannis et al. 2014), and not just from the eight year as occurred in this experiment (Sect. 2.1).

Thus, three additional scenarios of mango production for an 8-year-old orchard were analyzed: (1) the orchard is planted in an area occupied, for more than 20 prior years, by an annual crop (assumed to be melon, because of the large areas planted in the Sao Francisco Valley with this crop); (2) the growth regulator PBZ is applied to mango trees from the sixth to eighth year (the average yield of 8 years being 11,610 kg/ha, with 3 years each producing 30,961 kg/ha); and (3) the growth regulator is never applied (the average yield of 8 years being 4019 kg/ha, with 3 years each producing 10,718 kg/ha).

To understand the effect of uncertainty on the comparative evaluation between two treatments (A and B), the Monte Carlo method was applied with 1000 simulations. The impact of treatment A was considered higher than that of treatment B if $A–B > 0$, in at least 95% of the simulations. It was assumed that variables in inventories had a lognormal probability distribution. The geometric standard deviation of each variable was calculated by applying the Pedigree Matrix (Goedkoop et al. 2014).

It is important to notice that this study used agrochemical inventories (fertilizers, pesticides, and lime) from ecoinvent developed for other countries than Brazil. This choice was made because the inventory of agrochemicals produced in Brazil is not available in the national (SICV) and international databases. To account for this source of uncertainty, the following scores ware applied for Pedigree Matrix indicators in the ecoinvent inventories: 1 (verified data based on measurements) for "reliability," 1 (representative data from all sites relevant) for "completeness," 1 (less than 3 years of difference to the time period of the dataset) for "temporal correlation," 5 (data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) for "geographic correlation," and 3 (data from processes and materials under study but from different technology) for "further technological correlation".

3 Results

3.1 Step 1: assessment of the agronomic performance of cropping systems for mango production

The statistical analysis showed that the best yields were from T1, T2, T4, and T5 (see Table 1) that used plant mixtures as cover crops. Considering that these best treatments were similar in terms of yield, one of them (T4) was selected for the economic and environmental assessments. T6 was also selected for comparison with T4 because it represents the conventional mango production system in the region.

The variance analysis showed that mango yield was affected by the type of cover crop (plant mixtures or spontaneous vegetation) and production year (2015, 2016, or 2017), but not by soil management (tillage and no tillage) (P value < 0.05 in Table 2). Thus, treatments with the same cover crop and different soil management systems (T1 and T4, T2 and T5, and T3 and T6) presented no yield differences.

However, there were significant interactions of cover crops with soil management and of cover crop with time (Table 2). Analyzing the interaction of cover crop and soil management (Table 3), there was a significant difference in the average yields of treatments with plant mixtures (T1 and T4, T2 and T5) and those with spontaneous vegetation (T3 and T6). Comparing T2 and T5 better yields occurred in the no-tillage system, while comparing T3 and T6, the tillage system had better yields. The yields of T1 and T4 were similar in the two soil management systems.

The interaction of cover crop and time showed that all cover crops (T1 and T4, T2 and T5, and T3 and T6) significantly increased their yield in 2017 (Table 3). The higher yield in 2017 was due to the application of growth regulator, not used in previous years. In previous years, the treatments with plant mixtures (T1 and T4, T2 and T5) resulted in higher, but not significantly different, yields than those with spontaneous vegetation (T3 and T6).

Table 3 Annual mango yield in long-term field experiment

Cover crop	No tillage $t\ ha^{-1}$	Tillage	Mean
T1 and T4	16.12Aa	17.01Aa	16.57a
T2 and T5	16.13Aa	14.67Bab	15.40a
T3 and T6	8.87Bb	12.21Ab	10.54b
	2015	2016	2017
T1 and T4	8.38Ba	10.63Ba	30.69Aa
T2 and T5	8.15Ba	7.98Bab	30.07Aa
T3 and T6	6.05Ba	6.42Bb	19.15Ab
Mean	7.53B	8.34B	26.64A

Means followed by the same letters, uppercase (A and B) in rows and in lowercase (a and b) columns, do not differ among themselves ($P \leq 0.05$) by Tukey's test. T1–75% leguminous species + 25% grass and oilseed species, and no-tillage; T2–25% leguminous species + 75% grass and oilseed species, and no-tillage; and T3-spontaneous vegetation, and no-tillage; T4–75% leguminous species + 25% grass and oilseed species, and tillage; T5–25% leguminous species + 75% grass and oilseed species, and tillage; and T6-spontaneous vegetation, Values represent the average to the same plant mix treatment

NT average of the no-tillage treatments, *Average T* average tillage treatments

3.2 Step 2: assessment of economic performance

The economic analysis showed that profits are expected to occur from year 9 onwards, in both treatments (Table 4). From year 10 onwards, the profit in T4 becomes higher than in T6. In 30 years (expected orchard life time), T4 generates a profit that is 44% higher than T6.

T4 generated higher revenue than T6 (representing the conventional system). However, until year 8, the revenue from mango commercialization was not enough to cover all expenses related to the purchase of inputs and services. In the eighth year, production in T4 more than tripled with the use of the growth regulator, guaranteeing sufficient revenue to cover the costs, increase revenue, and generate profit. Production in T6 also increased in the eighth year, albeit to a lesser extent.

The production costs in T4 were primarily payments for field services, including the hoeing of the plant mixtures (manual trimming in Table 4) and application of pesticides (mechanical spraying). Purchases of high-quality seeds for the plant mixtures and of fertilizers were the main costs in this treatment. The application of the growth regulator to mango trees was less than 1% to the total costs, but increased revenue by 54%, thus being highly economically advantageous.

In T6, service costs were a higher share (76%) of the total costs than in T4. This was because the only aim of T6 was to cultivate mango, with no investment in improved soil quality between the lines of mango trees. The main services contributing to total costs were the same as in T4.

Table 2 Analysis of variance of mango yields, considering cover crops and soil management

	Degrees of freedom	Sum of square	Mean square	Statistical F	p value
Management	1	15.33	15.335	1.6261	0.2077
Cover crop	2	490.24	245.120	25.9925	< 0.0001
Time	2	5605.99	2802.996	297.2289	< 0.0001
Management * Cover crop	2	68.84	34.420	3.6499	0.0326
Management * Time	2	28.95	14.473	1.5347	0.2248
Cover crop * Time	4	282.42	70.604	7.4868	0.0001
Management * Cover crop *Time	4	33.50	8.376	0.8882	0.4774
Error	54	509.24	9.430		
Total	72	21,490.07			

Table 4 Economic analysis of treatments selected for one hectare of the orchard with mangoes

		Alternative system (T4)							Conventional system (T6)						
		Years 1 to 7		Year 8		Total in 8 years (US$)	Total in 30 years (US$)	%	Years 1 to 7		Year 8		Total in 8 years (US$)	Total in 30 years (US$)	%
Specification	Unit	Amount	Total (U$)	Amount	Total (U$)				Amount	Total (U$)	Amount	Total (U$)			
Services			*13,716.49*		*2562.20*	*16,278.69*	*72,647.04*	*54.04*		*13,897.66*		*2652.78*	*16,550.44*	*74,911.61*	*75.75*
Plowing and harrowing	MT	4.5	160.14	0	0.00	160.14	160.14	0.12	4.5	160.14	0	0.00	160.14	160.14	0.16
Limestone distribution	MT	2	64.70	0	0.00	64.70	64.70	0.05	2	64.70	0	0.00	64.70	64.70	0.07
Marking sowing grooves	MD	1	12.94	0	0.00	12.94	12.94	0.01	1	12.94	0	0.00	12.94	12.94	0.01
Making sowing grooves	MD	14	181.17	0	0.00	181.17	181.17	0.13	14	181.17	0	0.00	181.17	181.17	0.18
fertilizer distribution	MD	3	38.82	0	0.00	38.82	38.82	0.03	3	38.82	0	0.00	38.82	38.82	0.04
Planting and replanting	MD	4	51.76	0	0.00	51.76	51.76	0.04	4	51.76	0	0.00	51.76	51.76	0.05
Sowing mix of seeds	MT	16	517.62	0	0.00	517.62	517.62	0.39	16	517.62	0	0.00	517.62	517.62	0.52
Mowing/harrowing	MT	42	1358.74	6	194.11	1552.85	5823.18	4.33	42	1358.74	6	194.11	1552.85	5823.18	5.89
Mowing/harrowing	MD	156	2018.70	30	388.21	2406.91	10,947.57	8.14	156	2018.70	30	388.21	2406.91	10,947.57	11.07
Hoeing mango trees	MD	60	776.42	0	0.00	776.42	776.42	0.58	60	776.42	0	0.00	776.42	776.42	0.79
Pesticide application	MT	60	1941.06	12	388.21	2329.27	10,869.93	8.09	60	1941.06	12	388.21	2329.27	10,869.93	10.99
Pesticide application	MD	13	201.87	0	0.00	201.87	201.87	0.15	13	201.87	0	0.00	201.87	201.87	0.20
Formicide application	MD	4	51.76	0	0.00	51.76	51.76	0.04	4	51.76	0	0.00	51.76	51.76	0.05
Topdressing fertilization	MD	60	776.42	0	0.00	776.42	776.42	0.58	60	776.42	0	0.00	776.42	776.42	0.79
Training pruning	MD	32	414.09	0	0.00	414.09	414.09	0.31	32	414.09	0	0.00	414.09	414.09	0.42
Pruning of fruiting	MD	60	776.42	30	388.21	1164.64	9705.29	7.22	80	1035.23	40	517.62	1552.85	12,940.39	13.08
Panicle cleaning	MD	8	103.52	4	51.76	155.28	1294.04	0.96	8	103.52	4	51.76	155.28	1294.04	1.31
Application of growth regulator	MD	4	51.76	0	0.00	51.76	51.76	0.04	4	51.76	0	0.00	51.76	51.76	0.05
Protection of fruit	MD	12	155.28	6	77.64	232.93	1941.06	1.44	6	77.64	3	38.82	116.46	970.53	0.98
Irrigation	MD	84	1086.99	12	155.28	1242.28	4658.54	3.47	84	1086.99	12	155.28	1242.28	4658.54	4.71
Harvest	MD	50	647.02	25	323.51	970.53	8087.75	6.02	50	647.02	25	323.51	970.53	8087.75	8.18
Mango tree shoring	MD	12	155.28	6	77.64	232.93	1941.06	1.44	12	155.28	6	77.64	232.93	1941.06	1.96
Transport of inputs	MT	60	1552.85	8	207.05	1759.89	6314.91	4.70	60	1552.85	8	207.05	1759.89	6314.91	6.39

Table 4 (continued)

		Alternative system (T4)							Conventional system (T6)						
		Years 1 to 7		Year 8		Total in 8 years (US$)	Total in 30 years (US$)	%	Years 1 to 7		Year 8		Total in 8 years (US$)	Total in 30 years (US$)	%
Specification	Unit	Amount	Total (U$)	Amount	Total (U$)				Amount	Total (U$)	Amount	Total (U$)			
Production transportation	MT	24	621.14	12	310.57	931.71	7764.24	5.78	24	621.14	12	310.57	931.71	7764.24	7.85
Inputs			11,574.35		2182.60	13,756.95	61,774.06	45.96		2779.67		922.05	3701.73	23,986.92	24.25
Seedlings	Unit	250	323.51	0	0.00	323.51	323.51	0.24	250	323.51	0	0.00	323.51	323.51	0.33
Energy for irrigation	mil	m^3	39.53	1150.95	4.51	131.31	1282.26	41- 71.- 14	3.10	39.53	1150.95	4.51	131.31	1282.26	41- 71.- 14
4.22															
Fertilizers	kg or L	3592.46	1154.80	2363.54	747.04	1901.84	18,336.76	13.64	3592.47	1154.80	2363.54	747.04	1901.84	18,336.76	18.54
Neutral detergent	L	1.2	0.78	0	0.00	0.78	0.78	0.00	1.2	0.78	0	0.00	0.78	0.78	0.00
Insecticides	kg or L	1.31	29.47	0.2	3.42	32.90	108.20	0.08	1.31	29.47	0.2	3.42	32.90	108.20	0.11
Fungicides	kg or L	4.27	61.87	1.2	11.16	73.03	318.58	0.24	4.27	61.87	1.2	11.16	73.03	318.58	0.32
Herbicide	kg or L	4.1	29.18	0	0.00	29.18	29.18	0.02	4.1	29.18	0	0.00	29.18	29.18	0.03
Growth regulator	kg or L	0	0	3	29.12	29.12	669.67	0.50	0.00	0.00	3	29.12	29.12	669.67	0.68
Mix of seeds	kg	3765.16	8823.79	537.88	1260.54	10,084.34	37,816.26	28.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total cost			25,290.85		4744.79	30,035.64	134,421.10	100.00		16,677.33		3574.83	20,252.17	98,898.53	100
Total revenue			9287.48		14,322.97	23,610.46	338,715.90			6781.85		10,159.89	16,941.73	240,459.20	
Profit (revenue—Cost)			− 16,003.36		9578.18	− 6425.18	204,294.79			− 9895.49		6585.05	− 3310.44	141,560.67	

MD man day, *MT* machine time

3.3 STEP 3: environmental performance

3.3.1 Carbon footprint

Treatment T4 had a 16% smaller carbon footprint than T6. The values for climate change were negative for both T4 and T6 (Fig. 3). The process responsible for these negative carbon-equivalent outcomes was the land use change (Figure D1, Annex D in the supplementary material). Additional carbon stocks in the mango trees and in the soil were higher than the GHG emissions from all the processes considered in this mango study.

Treatment T4 stocked a higher carbon content in the orchard (− 6964.02 kg CO_2/ha; in Table B1, Annex B in the supplementary material) than T6 (− 4590.41 kg CO_2/ha; in Table B1). Although T4 also led to higher yield (6379.56 kg/ha; Table B1) than T6 (4577.67 kg/ha; Table B1), the carbon footprint of mango from T4 was lower per kilogram of mango (higher negative value in Fig. 3) than from T6.

3.3.2 Water footprint

T4 had a smaller (ranging from 16 to 137%, according to the impact categories) water footprint than T6 (Fig. 4). Crop production was the process that mostly contributed to the impact categories related to water footprint (Figures D2 to D7, Annex D in the supplementary material). For freshwater eutrophication, human toxicity (especially for non-cancer effects), and water scarcity, the production of synthetic fertilizers was another major contributor.

Synthetic fertilization and agriculture operations were the key activities resulting in emissions during crop production. The heavy metal emissions associated to urea and ammonium nitrate life cycle contribute to the human toxicity and ecotoxicity potentials. Phosphorous compounds from the applied ammonium phosphate and phosphoric acid fertilizers may also be transported to water bodies with soil particles in the erosion process, leading to freshwater eutrophication. Agricultural operations, especially the application of pesticides, required fossil fuels and machinery and so these production processes also raised the potential human toxicity.

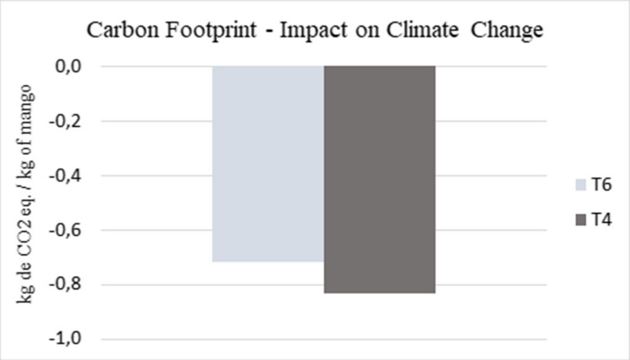

Fig. 3 Carbon footprint of mangoes produced in T4 (mango trees intercropped with cover crops) and T6 (mango trees intercropped with spontaneous vegetation) nu

Regarding water scarcity, the irrigation process demanded the highest amount of water in the product system. This affects water scarcity in the semi-arid region where the experimental station and most of the Brazilian mango production are located. However, at national level, Brazil has one of the lowest factors for water scarcity of the world (AWARE factor is 2.6 for agriculture processes), resulting in that the impact of irrigation on water scarcity contributed to only 25% of T4 final impact. On the other hand, fertilizer production contributed more to water scarcity values (47% in T4) because of the higher scarcity in Europe (AWARE factor is 5.95 for non-agriculture processes), despite lower water consumption.

For marine eutrophication, the nitrate emissions from fertilizer use in crop production caused this impact in T6. In T4, nitrous oxide emissions from burning part of the Caatinga vegetation during land use change accounted for this impact. In T4, there was no nitrate emission at crop production (Table B1, Annex B in the supplementary material) because this cropping system was in nitrogen equilibrium. The leguminous species of the plat mixture fixed nitrogen from the air, requiring less use of fertilizers to attend the total nitrogen requirement of the plants (mango trees and plant mixture).

3.3.3 Scenario analysis

Scenario analysis was applied to T4, since it had the best carbon and water footprints. Scenario 1 (land use change from annual to permanent crop production) reduced both carbon and water footprints in T4 (Fig. 5). Scenario 3 (no use of growth regulator) decreased the carbon footprint but increased the categories analyzed in the water footprint. Scenario 2 was the best one for water footprint but somewhat increased the carbon footprint, although the impact value for climate change remained negative.

Regarding carbon footprint, scenarios 1 and 3 led to a reduction in the impact of mango production on climate change compared to the reference situation. Scenario 1 resulted in the largest reduction in the impact (78%) because there were no carbon losses but gains through storage in the cover crop phytomass and soil, thus reducing overall GHG emissions. In scenario 3, the growth regulator was not used, resulting in lower GHG emissions from its non-production. In scenario 2, the growth regulator was applied, resulting in higher GHG emissions from its production.

Regarding water footprint, the impacts (per kg) were reduced by more than 20% in scenario 2 when the growth regulator was used from the sixth year onwards, leading to higher yield. In scenario 1, the lower emissions of direct N_2O and indirect NH_4 and NO_3 reduced this impact. On the other hand, the non-use of the growth regulator (scenario 3) increased all

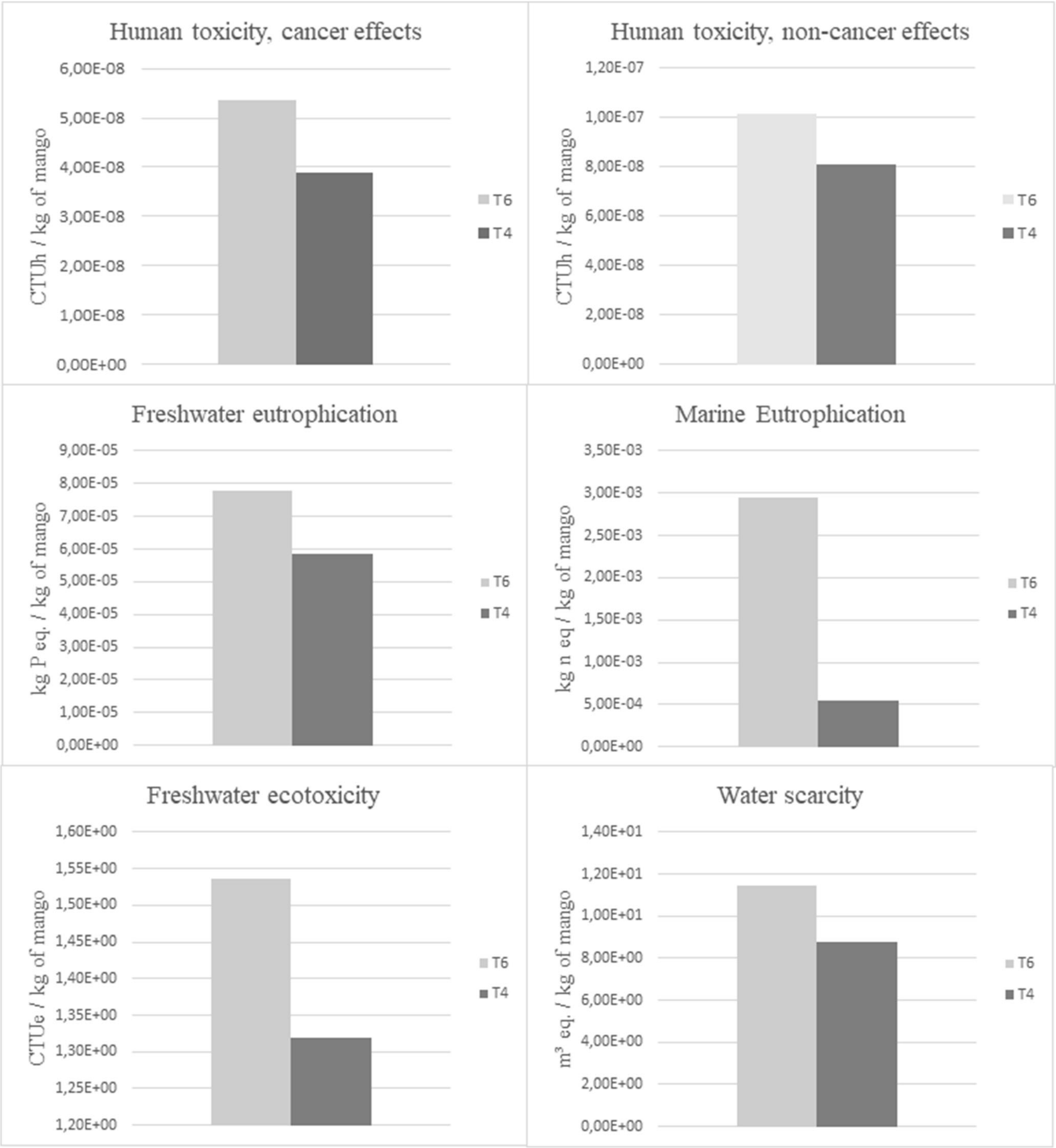

Fig. 4 Mango water footprint profile for T4 (mango trees intercropped with cover crops) and T6 (mango trees intercropped with spontaneous vegetation)

impacts related to water (except marine eutrophication) mainly due to the lower yield.

3.3.4 Uncertainty analysis

Regarding carbon footprint, although T4 performed better than T6 for climate change, the difference between treatments was not significant (T4 < T6 in only 72% of the 1000 simulations; Fig. 6). For water footprint, the impact of T4 was significantly lower than T6 in the categories of marine and freshwater eutrophication, and human toxicity, cancer effects. For the other water footprint categories, the impact values did not differ significantly between treatments.

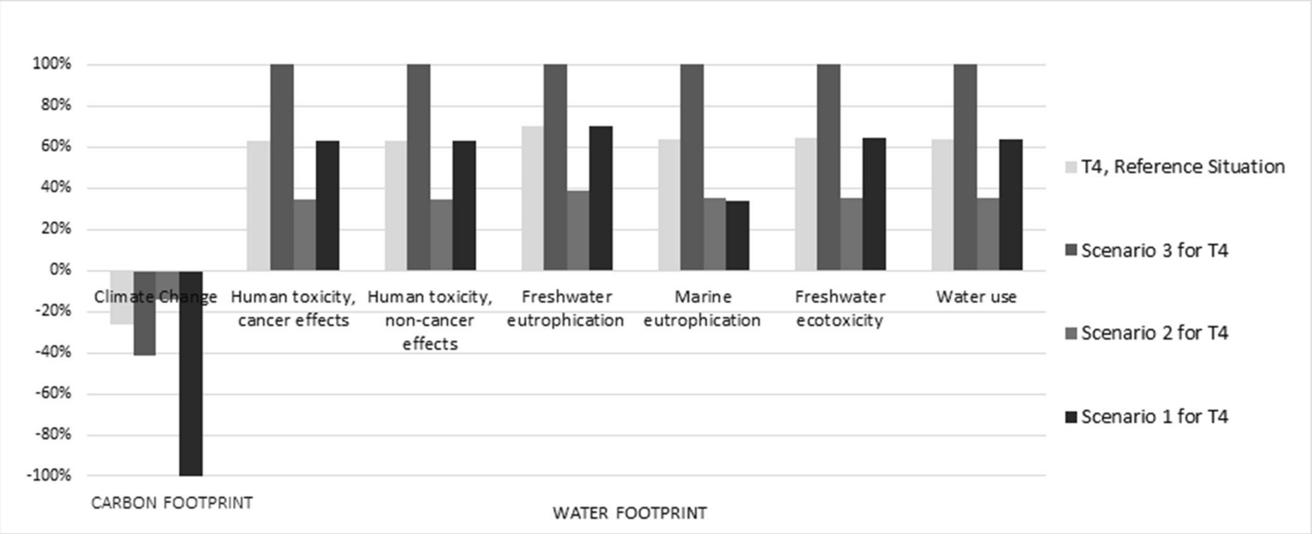

Fig. 5 Carbon and water footprints in T4 (mango trees intercropped with cover crops), comparing different crop production scenarios with the reference situation

4 Discussion

Considering the environmental-economic analysis carried out in this study, two questions emerge for discussion: is this experimental approach suitable for selecting cropping systems? Which mango cultivation system is more sustainable?

4.1 Suitability of the proposed approach

The approach applied in this study to evaluate alternative mango systems experimentally is innovative, facilitates the evaluation of many crop treatments, and can be easily applied in the study of other in-development cropping systems. The two-step procedure based on first selecting best and worst cultivation systems, according to yield, allowed reduction of the necessary number of economic and environmental evaluations from six to two.

Economic and environmental analysis requires collection of much field and market data: the masses of inputs and outputs as well as the costs of inputs and services. Therefore, the proposed strategy substantially reduces the amount of data and time necessary to evaluate the performance of alternative cropping system and select the best performing one. This issue is especially relevant when analyzing perennial crops that require data collection over many years, e.g., to account for all

Fig. 6 Uncertainty when comparing the carbon and water footprints of T4 (mango trees intercropped with cover crops) and T6 (mango trees intercropped with spontaneous vegetation)

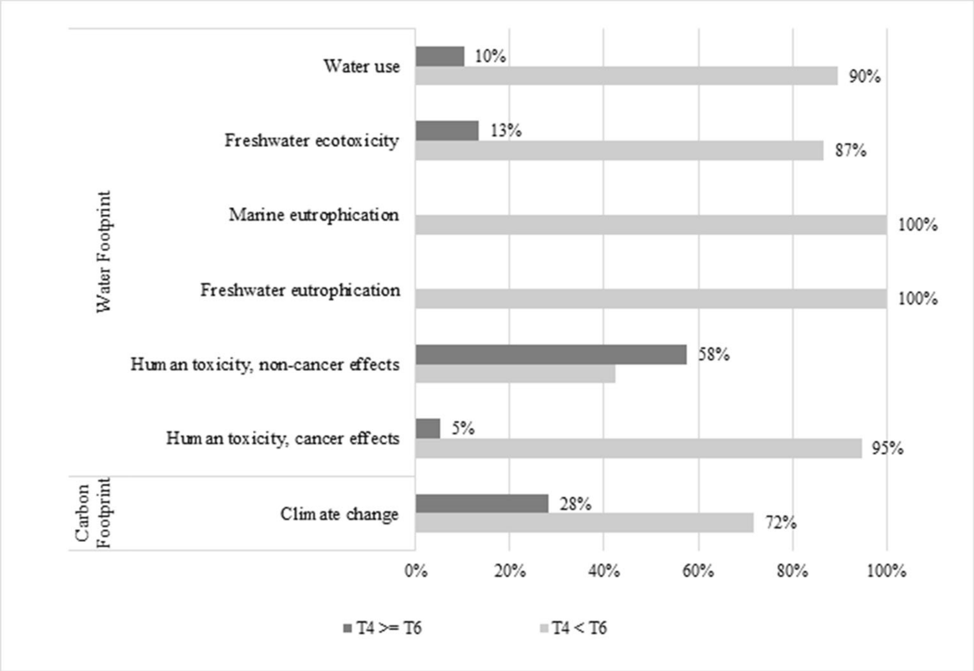

Table 5 Comparison of alternative and conventional (from literature) system per kilogram of mango

Footprint/impact categories	Unit	T4, 30 years (scenario 4)	Carneiro et al. (2019)
Carbon footprint			
Climate change	kg CO_2 Eq	− 4.32E−02	1.30E−01
Water footprint			
Human toxicity, cancer effects	CTUh	1.95E−08	8.33E−09
Human toxicity, non-cancer effects	CTUh	2.52E−08	7.25E−08
Freshwater eutrophication	kg P Eq	2.26E−05	2.33E−03
Marine eutrophication	kg N Eq	5.5E−04	1.41E−03
Freshwater ecotoxicity	CTUe	5.17E−01	1.09E+00
Water scarcity	m^3	2.82E+00	7.44E−01

stages of the orchard life cycle, as indicated by Cerutti et al. (2014) and followed in this study.

The few studies applying LCA in the analysis of experimental cropping systems can be partly explained by the difficulty in compiling all the data necessary for evaluating each treatment. As already commented, reduction in the number of options fully analyzed reduces this difficulty. Another reason is that, despite LCA being increasingly applied to the assessment of cropping systems, models for estimating the nitrogen and phosphorous emissions of different cropping systems need development (Meier et al. 2015).

The main shortcomings of the environmental approach proposed in this study are that important agricultural impact categories were not included in the analysis. According to Nemecek et al. (2011a), LCA of agriculture systems should consider, at least, the impacts on global warming (climate change), eutrophication, toxicity, biodiversity loss, and soil quality. Biodiversity loss and soil quality were not included in the study of carbon and water footprints. Soil quality, measured by soil organic matter, is indirectly considered if land use change is accounted for in the LCA assessment. In this study, the soil carbon of the compared systems was measured and directly influenced the lower impacts on climate change (carbon footprint) of the alternative system (T4). However, no biodiversity impacts were evaluated.

In the context of this article, the proposed approach initially allowed differentiating two groups of treatments, one representing alternative soil management (T1, T2, T4 and T5) and the other conventional management (T3 and T6). One treatment from each group was selected for assessing the economic-environmental performance, reducing in 67% the number of evaluated treatments. This reduction leads to less efforts regarding collecting and processing inventory data, making this study more time and cost efficient.

4.2 Choice of mango cultivation system

Based on this evaluation of the agronomic, economic, and environmental performances of mango production systems, a system that intercrops mango trees with plant mixtures, composed of leguminous and non-leguminous seeds, better contributes to long-term crop environmental-economic performance. This alternative system may use either 75% of leguminous or 25% of non-leguminous plants or vice-versa, and either tillage or no tillage for soil management. It produces higher biomass above and below ground, as well as higher nutrient accumulation, when compared to spontaneous vegetation (Brandão et al. 2017a). The nutrients are slowly liberated to the soil, positively affecting mango yields and profits, while lowering environmental impacts.

The high yields of the tested plant mix treatments (T1 and T4 and T2 and T5) in 2017 (30 t/ha) were above the Brazilian average (17.5 t/ha) (IBGE 2020). The lower yields under all treatments, in 2015 and 2016, were similar to those in India (7.3 t/ha), China (8.2 t/ha), and Mexico (8.9 t/ha) (FAO 2017).

It is noteworthy that the amount of carbon stored in the soil can be expected to increase in the years to come, under the experimental treatments with plant mixtures intercropped with mango, increasing the carbon footprint advantage of the alternative system relative to the conventional systems. Poeplau and Don (2015) quantified the potential of cover crops, applied as green manure, to increase soil organic carbon (SOC) stock, and concluded that 50% of the gain in carbon stocks is expected to occur in the first two decades after cover crops are planted, while lasting for more than 100 years.

Cover crops may, however, increase the overall demand for irrigation when the rainfall does not meet the water demand of both mango trees and cover crops, as is usually the case in semi-arid regions. However, previous studies have indicated that conservational tillage and the appropriate mix of plants cultivated as cover crops can be a good option for increasing soil water retention and carbon storage, without affecting the yield of the cash crop. García-González et al. (2018) found that reducing tillage in the cover crop area reduced the demand for additional water in a 10-year crop rotation experiment, applying irrigation, in semi-arid Spain. Lampurlanés et al. (2016) demonstrated that under semi-arid conditions in northeast Spain, soil water storage increased with the use of conservation tillage. Garcia-Franco et al. (2018) concluded that the choice of cover crops with different root depths, as in the plant mix used in this mango study, is also important to prevent higher water demand in irrigated intercropped systems in dry land areas. Mitchell et al. (2017), evaluating a 15-year-old experiment in the dry area of California, concluded that the association of no-tillage and irrigated cover crops improved soil health (chemical, physical, and biological properties) and maintained the yield of the cash crop.

From this analysis, it seems worthwhile to invest in the alternative mango system based on no tillage of cover crop phytomass (reduced tillage in T1). This treatment had no significant difference in yield (16 t/ha) from T4 (17 t/ha). Furthermore, the reduced tillage leads to lower costs and emissions from diesel burning, positively affecting T1's economic and environmental performances.

The results also showed that the economic and environmental performances of mango production increased when growth regulator was applied to mango trees from the beginning of the orchard production stage (sixth year onwards). Although this leads to higher costs for mango farmers as well as higher GHG and nitrogen emissions related to the regulator production process, the higher yields resulting from its use generated higher revenues and compensated most of the environmental impacts when calculated per kilogram of mango.

4.3 Comparison with other mango footprint studies

In order to compare the environmental performance of mangoes produced in T4 with the performance of mango farms in the São Francisco Valley, a simulation was performed assuming that the same inputs and outputs are used from year 8 until the orchard is renewed in year 30. This comparison showed that T4 offers a better carbon footprint and overall water footprint (except for the category of human toxicity, cancer) than the conventional system evaluated by Carneiro et al. (2019), adopting the same impact methods used in this study (Table 5).

Carneiro et al. (2019) observed that the carbon stock in a mango orchard was superior to that of the *Caatinga* biomass. However, in a monocrop mango system, the GHG emissions were higher than the amount of carbon stocked in the orchard, generating a carbon footprint of 0.13 kg CO_2 Eq/kg of mango. The intercropping of mango with cover crops, investigated in this study, increased carbon storage and resulted in a negative carbon footprint.

The carbon stock held in the cultivation of fruit trees is especially important in semi-arid regions, where perennial crops may increase the carbon stock in the biomass, relative to savanna vegetation. However, many studies assessing the carbon footprint of fruits produced in semi-arid regions have disregarded the carbon balance related to land use change (Marras et al. 2015; Vinyes et al. 2017).

Finally, it was observed in this study that intercropping mango trees with cover crops reduced the amount of synthetic nitrogen fertilizer applied in the orchard, reducing the carbon and water footprint of mango production. This was due to the greater contribution of organic matter by the plant mixtures (283 kg N organic/ha in T4) and their fixation of nitrogen from the air.

5 Conclusion

This study presented an agile approach for assessing the environmental-economic performance of cropping systems, based on agronomic, economic, and environmental criteria. When applied to a mango experiment in Brazil, this approach reduced the data required for performing this type of assessment, while still allowing the identification of best performing cropping system. The results from this study showed that the proposed approach is time and cost efficient, being suitable for application in other crop experiments.

The application of this approach for evaluating alternative mango systems showed that treatments with plant mixtures as cover crops between lines of mango trees, independent of the type of mix used (75% leguminous and 25% non-leguminous or conversely) or the soil management applied (tillage or no tillage of plant mix phytomass), achieved better performance. Furthermore, this study showed that the use of a growth regulator on the mango trees from the beginning of mango production (sixth year) increases yield and the economic-environmental performance of T4 in 30 years. The higher yields achieved with regulator use compensated the higher costs and potential environmental impacts related to its production.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Barão L, Alaoui A, Ferreira C, Basch G, Schwilch G, Geissen V, Sukkel W, Lemesle J, Garcia-Orenes F, Morugán-Coronado A, Mataix-Solera J, Kosmas C, Glavan M, Pintar M, Tóth B, Hermann T, Vizitiu OP, Lipiec J, Reintam E, Xu M, Di J, Fan H, Wang F (2019) Assessment of promising agricultural management practices. Sci Total Environ 649:610–619

Basset-Mens C, Vannière H, Grasselly D, Heitz H, Braun A, Payen S, Koch P, Biard Y (2016) Environmental impacts of imported and locally grown fruits for the French market: a cradle-to-farm-gate LCA study. Fruits 71(2):93–104

Boulay AM, Bare J, Benini L, Berger M, Lathuillière MJ, Manzardo A, Margni M, Motoshita M, Núñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S (2018) The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int J Life Cycle Assess 23(2):368–378

Brandão SS, Salviano AM, Olszevski N, Giongo V (2017a) Green manure contributing for nutrients cycling in irrigated environments of the Brazilian semi-arid. Journal of Environmental Analysis and Progress 2(4):519–525

Brandão SS, Giongo V, Olszevski N, Salviano AM (2017b) Plant mix and soil management systems changing soil quality and mango productivity. Revista Brasileira de Geografia Física 10(4):1079–1089

Carneiro JM, Dias AF, Barros VS, Giongo V, Matsuura MISF, Figueirêdo MCB (2019) Carbon and water footprints of Brazilian mango produced in the semi-arid region. Int J Life Cycle Assess 24(4):735–752

Cerutti AK, Beccaro GL, Bruun S, Bosco S, Donno D, Notarnicola B, Bounous G (2014) LCA application in the fruit sector: state of the art and recommendations for environmental declarations of fruit products. J Clean Prod 73:125–135

Chatzivagiannis MA, São José AR, Bomfim MP, Oliveira Junior MX, Rebouças TNH (2014) Flowering and yield of the mango fruits 'bourbon', 'palmer' and 'rosa' with use of paclobutrazol. Rev Iber Tecnología Postcosecha 15(1):41–47

Deytieux D, Munier-Jolain N, Caneill J (2016) Assessing the sustainability of cropping systems in single-and multi-site studies: a review of methods. Eur J Agron 72:107–126

EPD International AB (2019) Fruits and Nuts: Product Category Classification: UN CPC 013. Version 1.01. https://www.environdec.com/PCR/Detail/?Pcr=14175

Falcone G, Stillitano T, Montemurro F, De Luca AI, Gulisano G, Strano A (2019) Environmental and economic assessment of sustainability in Mediterranean wheat production. Agron Res 17(1):60–76

Faria CMB, Soares JM, Leão PCS (2004) Adubação verde com leguminosas em videira no Submédio São Francisco. Revista Brasileira de Ciência do Solo 28(4):641–648

Faria CMB, Costa ND, Faria AF (2007) Atributos químicos de um Argissolo e rendimento de melão mediante o uso de adubos verdes, calagem e adubação. Revista Brasileira de Ciência do Solo 31:299–307

Filgueiras HAC, Menezes JB, Amorim TBF, Alves RE, Castro EB (2000) Características da fruta para exportação [Caracteristics for fruits exported]. In: Filgueiras HCA (ed) Manga pós-colheita [Mango post-harvesting]. Embrapa Comunicação para Tranferência de Tecnologia, Brasília, pp 14–21

Food and Agriculture Organization (FAO) (2009) Global agriculture towards 2050. FAO, Rome

Food and Agriculture Organization (FAO) (2017) Faostat: crop production. http://www.fao.org/faostat/en/#data. Accessed 01 June 2019

Garcia-Franco N, Hobley E, Hübner R, Wiesmeier R (2018) Climate-smart soil management in semiarid regions. In: Munoz M, Zornoza R (eds) Soil management and climate change: effects on organic carbon, nitrogen dynamics, and greenhouse gas emissions. Academic, Cambridge, pp 349–368

García-González I, Hontoria C, Gabriel JL, Alonso-Ayuso M, Quemada M (2018) Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. Geoderma 322:81–88

Giongo V, Salviano A, Santana M, Costa ND, Yuri JE (2016) Soil management systems for sustainable melon cropping in the sub-median of the São Francisco Valley. Revista Caatinga 29:537–547

Goedkoop M, Oele M, Vieira M, Leijting J, Ponsioen T, Meijer E (2014) SimaPro tutorial. PRé-Consultants, Amersfoort

Gomes TCA, Silva JAM, Soares BEM, Silva MSL (2004) Decomposition and nutrient release patterns of the green manure phytomass in irrigated mango orchard. Acta Hortic 645:183–188

International Organization for Standardization (ISO) (2006a) ISO 14040:2006—environmental management—life cycle assessment—principles and framework. ISO, Geneva

International Organization for Standardization (ISO) (2006b) ISO 14044:2006—environmental management—life cycle assessment—requirements and guidelines. ISO, Geneva

International Organization for Standardization (ISO) (2013) ISO 14067:2013—greenhouse gases—carbon footprint of products—requirements and guidelines for quantification and communication. ISO, Geneva

International Organization for Standardization (ISO) (2014) ISO 14046:2014—environmental management–water footprint principles— requirements and guidelines. ISO, Geneva

International Panel on Climate Change (IPCC) (2006) Guidelines for national greenhouse gas inventories. IPCC, Geneva

International Panel on Climate Change (IPCC) (2013) Fifth assessment report. IPCC, Geneva

JRC (Joint Research Centre of the European Commission), IES (Institute for Environment and Sustainability) (2011) International Reference Life Cycle Data System (ILCD) Handbook: Recommendations for Life Cycle Impact Assessment in the European context. First edition November 2011. EUR 24571 EN. Luxemburg. Publications Office of the European Union

Lampurlanés J, Plaza-Bonilla D, Álvaro-Fuentes J, Cantero-Martínez C (2016) Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crop Res 189:59–67

Lewis DG (1995) Análise de variância. Editora Harbra, São Paulo

MAPA (Ministry of Agriculture, Livestock and Food Supply) (2020) Agrostat database. http://indicadores.agricultura.gov.br/agrostat/index.htm. Accessed 21 Feb 2020

Marras S, Masia S, Duce P, Spano D, Sirca C (2015) Carbon footprint assessment on a mature vineyard. Agric For Meteorol 214(15):350–356

Matejovic I (1997) Determination of carbon and nitrogen in samples of various soils by the dry combustion. Commun Soil Sci Plant Anal 28(17–18):1499–1511

MCTI (Ministry of Science, Technology and Innovation) (2010) Inventário Brasileiro de Emissões Antrópicas por Fontes e Remoções por Sumidouros de Gases de Efeito Estufa não Controlados pelo Protocolo de Montreal. MCTI, Brasília

Meier MS, Stoessel F, Jungbluth N, Juraske R, Schader C, Stolze M (2015) Environmental impacts of organic and conventional agricultural products: are the differences captured by life cycle assessment? J Environ Manag 149:193–208

Mitchell JP, Shrestha A, Mathesius K, Scow KM, Southard RJ, Haney RL, Schmidt R, Munk DS, Horwath WR (2017) Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. Soil Tillage Res 165:325–335

National Mango Board (NMB) (2010) Sustainability assessment: baseline assessment findings & recommendations. Available from: <http://www.mango.org/Mangos/media/Media/Documents/Research%20And%20Resources/Research/Industry/Post-Harvest/Sustainability_Final_Report_Engpdf?ext=pdf>. Accessed: 15 Oct 2017

Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G (2011a) Life cycle assessment of Swiss farming systems: I. integrated and organic farming. Agric Syst 104:217–232

Nemecek T, Huguenin-Elie O, Dubois D, Gaillard G, Schaller B, Chervet A (2011b) Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agric Syst 104:233–245

Nemecek T, Bengoa X, Lansche J, Mouron P, Riedener E, Rossi V, Humbert S (2015) Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.0, July 2015, World

Food LCA Database (WFLDB), Quantis and Agroscope, Lausanne and Zurich, Switzerland

Nicki G (2016) The environmental pressures of eating a mango: a preliminary life cycle assessment of mango production in Taiwan. A&WMA ' s 109th Annual Conference & Exhibition. New Orleans, Louisiana

Pereira Filho A, Teixeira Filho J, Giongo V (2016) Nutrients dynamics in soil solution at the outset of no-till implementation with the use of plant cocktails in Brazilian semi-arid. Afr J Agric Res 11(4):234–246

Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops – a meta-analysis. Agric Ecosyst Environ 200:33–41

R Core Team (2015) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/. Accessed 03 June 2019

Ridoutt BG, Juliano P, Sanguansri P, Sellahewa J (2010) The water footprint of food waste: case study of fresh mango in Australia. J Clean Prod 18:1714–1721

Santos TL, Nunes ABA, Giongo V, Barros VS, Figueirêdo MCB (2018) Cleaner fruit production with green manure: the case of Brazilian melons. J Clean Prod 181:260–270

Silva MSL, Gomes TCA (2004). Manejo do solo [Soil management]. In Mouco MAC (ed) Cultivo da mangueira [Mango production]. Available at: http://www.cpatsa.embrapa.br:8080/sistema_producao/spmanga/socioeconomia.htm. Accesses 01 Apr 2019

Smith P, I H, Bustamante M, Sobocká J, Harper R, Pan G, West PC, Clark JM, Adhya T, Rumpel C, Paustian K, Kuikman P, Cotrufo MF, Elliott JA, McDowell R, Griffiths RI, Asakawa S, Bondeau A, Jain AK, Meersmans J, Pugh TA (2015a) Global change pressures on soils from land use and management. Glob Chang Biol 22:1008–1028

Smith F, Cotrufo C, Rumpel K, Paustian K, Kuikman PJ, Elliott JA, McDowell R, Griffiths RI, Asakawa S, Bustamante M, House JI, Sobocká J, Harper R, Pan G, West PC, Gerber JS, Clark JM, Adhya T, Scholes RJ, Scholes MC (2015b) Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. Soil 2:537–586

Souza Filho HD, Frigere T, Moreira A, Godoy R (2007) Produção de sementes de Guandu. Embrapa Pecuária Sudeste, São Carlos

Statsoft INC (2007) Statistic (data analysis software system), version 7

Tait PR, Saunders C, Guenther M (2015) Valuing preferences for environmental sustainability in fruit production by United Kingdom and Japanese consumers. J Food Res 4(3):46–55

The Brazilian Institute of Geography and Statistics (IBGE) (2020) Municipal agriculture production. https://ww2.ibge.gov.br/home/estatistica/economia/pam/2016/default.shtm. Accessed 21 Feb 2020

Valentini L, Oliveira LAA, Ferreira JM (2009) Produção de sementes de milho variedade para uso próprio em propriedades de microbacias hidrográficas. Programa Rio Rural-Manual Técnico, 15. Niterói- RJ

Vinyes E, Asin L, Alegre S, Asin L, Alegrec S, Pere M, Boschmonart J, Gasol CM (2017) Life cycle assessment of apple and peach production, distribution and consumption in Mediterranean fruit sector. J Clean Prod 149:313–320

Willekens K, Vandecasteele B, Buchan D, Neve S (2014) Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Appl Soil Ecol 82:61–71

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