Journal of Cleaner Production 112 (2016) 2505–2517

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental profile of green asparagus production in a hyper-arid zone in coastal Peru

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ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form
17 September 2015
Accepted 18 September 2015
Available online 9 October 2015

Keywords:
Cleaner production
Green asparagus
Irrigation
Life cycle assessment
Peru
Water use

ABSTRACT

The Peruvian coast has developed a robust agricultural sector despite the low average rainfall thanks to the availability of water resources from rivers and groundwater. In fact, this area has become one of the main producers of green asparagus worldwide due to the availability of water and the high yield rates that can be reached. However, irrigation and intensive agriculture constitute a significant threat to water depletion in the region, as well as to important changes in land use. In addition, the intensive use of fertilizers and plant protection agents can increase the amount of nutrients and/or toxic agents in river and in the soil. Hence, a Life Cycle Assessment study was conducted for an agricultural farm in Paracas that cultivates green asparagus for export to North America or Europe. The aim of the study was to understand the potential environmental impacts associated with the cultivation of this product in a hyper-arid area. Results showed a considerably lower water use in the cultivation site when compared to business-as-usual values for the region, due to the advanced irrigation system applied. Environmental impacts were strongly influenced by the high energy intensity linked to the production of inorganic fertilizers used on-site and, to a lesser extent, plant protection agents. Transport environmental burdens were also identified as important sources of environmental impact throughout the impact categories monitored, especially when airfreighted to the final country of destination. Finally, the use of methyl bromide to fumigate green asparagus at US customs implied a high burden in terms of ozone depletion. The results in this study intend to be a proxy to understand the specific hotspots linked to the production of green asparagus in Peru, as well as a way forward for local small- and medium-scale companies to get involved in the improvement of their ecological marketing strategies.

1. Introduction

Despite an important urbanization process in Peru in the past couple of decades, the agricultural and fishing sectors still represent 5.8% of Peruvian exports, and 24.2% of the active population was employed in the primary sector in 2012 (INEI, 2013, 2014a, 2014b). In fact, Peru has an important role worldwide in the production of agricultural products, not only in terms of bulk production, but also regarding the variety of products that grow in this multi-climate tropical nation. Given the existence of this climatic variability, agricultural landscapes can vary from endemic potato crops in the Andean highlands to irrigated agricultural farms along the arid Peruvian coast.

For instance, the provinces of Ica and Pisco (both in the region of Ica), 250 km South of Lima, have developed a robust agricultural sector despite the low average rainfall thanks to the availability of water resources from rivers and groundwater (Cárdenas, 2012; Oré and Damonte, 2014). However, irrigation and intensive agriculture constitute a significant threat to water depletion in the region, as well as engendering important changes in land use (Wiegers et al., 1999; Meyfroidt et al., 2010). In addition, the intensive use of fertilizers and plant protection agents can increase the amount of nutrients and/or toxic agents in rivers and in the soil (Huijbregts et al., 2000).

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http://dx.doi.org/10.1016/j.jclepro.2015.09.076
0959-6526/

Peru's agricultural sector is moderately to highly vulnerable, depending on the region, to the El Niño phenomenon, which periodically affects the country causing important disruptions in the countries otherwise fairly predictable climate (Hesse and Baade, 2009; Goldstein and Magilligan, 2011). In addition, Peru is listed as one of the countries with highest risks in terms of vulnerability to the effects of global warming according to the Intergovernmental Panel on Climate Change (IPCC). While many people may associate this vulnerability with greenhouse gas (GHG) emissions exclusively, the problem is more complex, since the consequences may also appear in the form of water scarcity, depletion of natural resources (e.g. anchoveta stocks) or land use changes (IPCC, 2007). Consequently, Peruvian producers are increasingly aware of the need to understand the environmental conditions they work in, including the environmental impacts that arise from their own local practices and production systems.

In this context, Life Cycle Assessment (LCA) has become one of the most important environmental assessment methodologies available in the literature to evaluate the life-cycle environmental impacts linked with a certain service, product or service (ISO, 2006a). Moreover, LCA can quantify environmental impacts for a wide range of environmental dimensions, including global warming, toxicity, use of resources or acidification, among others (Hellweg and Milà i Canals, 2014). Once focussed on industrial processes, it soon developed as an interesting tool to determine the environmental profile of agricultural products (Poritosh et al., 2009). Hence, numerous studies across the world have been published dealing with a variety of environmentally-relevant information. For instance, the most recurrent studies deal with the environmental monitoring of a certain agricultural product in order to understand the main energy or material flows responsible of the environmental impact, as a way to suggest improvement actions (Rugani et al., 2013).

However, most studies have focused on agricultural production systems in temperate areas of the world, namely Europe and North America, whereas the analysis of the environmental profile of agricultural crops in Latin America is currently underrepresented in the literature available (Reap et al., 2008). In this study, a green asparagus production site in the abovementioned province of Pisco (13°42′S; 76°12′W) was analyzed with the aim of understanding the environmental impacts of the cultivation of this crop under extreme climatic conditions. The study is justified in terms of the weight of Peruvian green asparagus production (i.e., 374,000 metric tons in 2013), being the second producer worldwide after China (INEI, 2014a). Moreover, green asparagus has shown to have a high nutrient/calorie ratio, and can help prevent cancer, ageing or cardiovascular diseases due to its high content in antioxidants, such as ascorbic acid or glutathione (Sun et al., 2007; Kim et al., 2009; Wang et al., 2011). Its healthful food characteristics imply that its cultivation and consumption will continue to increase in years to come. Hence, the identification of the environmental impacts linked to the cultivation of this vegetable is an important milestone in terms of sustainable production and consumption. Finally, beyond the nutritional and health benefits of this vegetable, the producer expressed interest in understanding the equilibrium between GHG emissions and water use at the site, without disregarding the impacts in other environmental aspects from a life-cycle perspective.

2. Materials and methods

2.1. Goal and scope

As previously mentioned, the main objective of this research was to evaluate the environmental profile related to the production of green asparagus in Ica (Peru). The aim of the study was oriented mainly towards the identification of the environmental hotspots throughout the production system, as well as suggesting a series of improvement measures to reduce the environmental burdens of the product under analysis. The study was carried out for four different years of cultivation (2010–2013), which represent the first four years of farming. This fact is of special interest considering that the crop yield curve will show an increasing trend throughout the years assessed. Consequently, the analysis of how this yield curve affects the environmental profile of the final product delivered will also be a matter of discussion. Nevertheless, results also present an estimation of selected environmental impacts in 2014, for which partial primary data regarding water and electricity use, as well as harvest yield were available, and 2015, which was based on current practices in years 2013 and 2014 and on the aid of the agronomic engineers working at the site (J.P.B., personal communication, January 2015).

For this case study the ISO standards specified in ISO 14040 and 14044 for LCA studies were followed (ISO, 2006a, 2006b). The function of the system was the delivery of green asparagus cultivated at the site to the main export destinations ready to supply the wholesalers. Hence, the selected functional unit (FU), which is the reference to which the material and energy flows are referred to (ISO, 2006b), was a 5 kg box of fresh green asparagus exported to the United Kingdom (UK) or the United States (US) by plane or transoceanic cargo at the port or airport of Callao – 12° 2′S; 77° 8′W (Peru), showing the function of delivering green asparagus ready for distribution to wholesalers in European and North American countries. The selection of the FU was based on the standard package dimensions and content, as described in the Peruvian technical specification for fresh asparagus packaging (NTP, 2013).

2.2. System boundaries

The production system analyzed included all the processes linked to the production of green asparagus in the cultivation site, such as field operations, soil management, fertilization or harvest operations, as well as post-harvest activities (i.e., storage and packaging). In addition, upstream processes were followed to account for the extraction of raw materials, production and distribution of a variety of materials used at the cultivation site, such as inorganic fertilizers, plant protection agents, packaging materials or diesel, among other inputs. Downstream processes included the freight operations from the gate of the cultivation site to the port of Callao. The system boundaries were not only limited to green asparagus freighting on Peruvian soil, but the impact of oceanic or airfreight to the final nations of destination were modelled considering the different modes of transport. Therefore, the analyzed system represents a cradle-to-gate approach in which the products are followed up to their departure from Peruvian soil and, in an extended manner, to their arrival in customs at the country of destination. Post-export operations, such as wholesaling, retailing or consumption were excluded from the system boundaries (see Fig. S1 in the Supplementary material for a graphical representation of the flow diagram for the modelled production system).

2.3. Data acquisition and quality

Primary data obtained for this study were acquired mainly from the producer (Table 1). In the first place, a questionnaire was developed by the LCA practitioners in order to obtain data regarding the main material and energy flows occurring at the cultivation site. Secondly, in several meetings with the technical staff from the agricultural company, the questionnaire was

Table 1
Operational characteristics of the cultivation site in the period 2010–2013.

	Unit	2010	2011	2012	2013	2014
Surface area	ha	120	120	120	120	120
Green asparagus yield	t/ha	–[a]	3.6	6.0	8.0	10.0
Total green asparagus production	t	–[a]	456	720	960	1200
Economic value	$/kg	–[a]	1.44	1.61	1.42	N/Av
Total green asparagus exports	t	–[a]	365	576	768	960

[a] 2010 was the seedling year. Therefore, no commercial harvest was performed in this first year of operation.

amended and, thereafter, the questionnaire was submitted for completion.

Regarding primary data, annual values in the period 2010–2013 were reported for crop yield, human labour, cultivated area, as well as a series of operational inputs, such as the amount of organic and inorganic fertilizers, plant protection agents, water use and the electricity required to pump water. In addition, field machinery, infrastructure of the cultivation site (i.e., irrigation system), as well as the packaging and distribution processes within Peruvian soil were also provided.

Background data were adapted from the available ecoinvent® 3.01 database (Weidema et al., 2013). For instance, in the case of electricity, the electricity production mix available in ecoinvent® for Peru was adapted to years 2010 and 2011 based on available data from the Ministry of Energy (Vázquez-Rowe et al., 2015). For years 2012 and 2013 the electricity mix was not available at the time of the study, so the last available year was assumed (2011). However, the observed tendency in the past decade is that the additional demand for electricity, which is currently growing at an average rate of approximately 4% per year, is met by an increase in the use of fossil fuels, mainly domestic gas. Hence, environmental impacts due to electricity consumption may be slightly underrepresented.

Peru does not produce inorganic fertilizers and most plant protection agents are imported from abroad. However, the producing country was known for all pesticides, thanks to the national inventory obtained from the Ministry of Agriculture (SENASA, 2014). Therefore, the ecoinvent® datasets per pesticide type were adapted to the specific energy characteristics of each country of production, as well as the freighting to Peru. Regarding inorganic fertilizers, the exact country of origin was unknown. However, a mass allocation per exporting nation was performed based on the data obtained from the Peruvian Ministry of Agriculture, as shown in Tables S1–S4 of the SM (Ministerio de Agricultura, 2011, 2012, 2013). This allowed modelling the fertilizer production system, which is highly energy-intensive, for each of these nations, rather than just using global data, by modifying and adapting energy and heat characteristics to national benchmarks.

Organic fertilizers, in contrast, were included in the study based on local characteristics. On the one hand, the NPK content of *guano* was modelled considering the official characteristics of the Peruvian government, in charge of its commercialization. Hence, a 12% content of N, 11% for P_2O_5 and 2.5% K_2O were taken into consideration, as well as the content of other nutrients such as CaO, MgO or S (Ministerio de Agricultura, 2015). On the other hand, a soil conditioner named *Avibiol*, which is of common use in Peru, was modelled following producer guidelines (Avibiol®, 2015).

Emissions linked to fertilization were adapted from a variety of bibliographical sources. In the first place, the emission factors considered in the ecoinvent® guidelines were taken into account for phosphorus emissions and for NO_x (Nemecek and Kägi, 2007). However, specific emission factors for tropical areas were taken into consideration for dinitrogen oxide (N_2O), NH_3 volatilization and NO_3 leaching (Bouwman et al., 2001; Marquina et al., 2013). Firstly, for N_2O an emission factor of 0.0078 (i.e., 0.78% of applied nitrogen is emitted as N_2O–N) was assumed based on the sandy characteristics of the cultivation site (Marquina et al., 2013). Secondly, for NH_3 the emission factors that were considered were 0.15 for synthetic fertilizers and 0.30 for organic N fertilizer based on the data provided by Bouwman et al. (2001). Finally, for NO_3 a leaching value of 0.30 was taken into account, since this is the default value for irrigated crops.

Regarding transport, trucks transporting the cargo to the port of Callao were modelled in terms of diesel consumption and emissions. It was assumed that the freight was transported in trucks that comply with the Euro III Directive, which happens to be the most advanced emission limit standard currently regulated in Peru. In addition, cooling agent emissions in these trucks was assumed to follow a similar pattern to those reported by Stemmler et al. (2004).

The quality of data was guaranteed by following the requirements fixed in the technical specification ISO/TS 14048/2002 (ISO, 2002). Consequently, the identification of temporal, spatial and technological issues has been described in previous sections. Similarly, completeness was attained through the compliance of the inventories with the Peruvian technical specifications for asparagus cultivation (NTP, 2003), processing (NTP, 2013) and transport (NTP, 2014). Consistency of the results was met, as aforementioned, in compliance with ISO 14040 and 14044 (ISO, 2006a, 2006b). The reproducibility of the study should be accomplished based on the description of the inventories in Section 2.4, as well as the modelling and computing guidance provided in Sections 2.5 and 2.6. Finally, precision of the inventory data, i.e., the degree of variability of data values, was not quantifiable due to the fact that one single dataset was included in the study. Having said this, lack of precision was counterbalanced through the computation of several years of activity, as well as with sensitivity analysis modelling.

2.4. Life cycle inventory

The Life Cycle Inventory (LCI) stage assembles data to cover the necessary inputs and outputs of a production system, including the use of resources and emissions (ISO, 2006b). The LCI was divided into 3 subsystems in order to provide a clear representation of the system assessed: i) cultivation and harvesting; ii) storage and packaging; and iii) national and international freight. Therefore, Tables 2–4 present the main inputs and outputs occurring in the different phases as referred to the FU.

2.5. Allocation and other assumptions

The only marketable product that was analyzed in the cultivation site is green asparagus intended for exportation. However, it should be noted that only 80% of the total harvest is finally destined to exports. In fact, 5% of the harvest yield corresponds to asparagus stumps that are collected at no cost for farmers to use as fodder. Moreover, an additional 15% of the harvest yield is constituted of green asparagus that due to its lower quality is sold to third parties

Table 2
Summary of the annual inventory data for subsystem I – agricultural stage (data per metric ton of harvested green asparagus).

	Unit	2011	2012	2013	2014
Inputs from the technosphere					
Fossil fuels					
Diesel consumption	kg	12.3	12.5	9.1	7.3
Organic fertilizers					
Guano	kg	43.9	0.0	0.0	0.0
Other organic fertilizer	L	0.0	0.0	12.5	10.0
Inorganic fertilizers					
Ammonium nitrate	kg	74.9	72.6	1.5	1.2
Phosphoric acid	kg	58.7	36.4	33.7	27.0
Potassium sulphate	kg	0.0	46.1	52.0	41.6
Magnesium sulphate	kg	20.4	45.6	12.7	10.2
Calcium nitrate	kg	15.2	11.3	4.5	3.6
Boric acid	kg	3.9	1.6	0.0	0.0
Urea – ammonium nitrate	L	0.0	0.0	80.3	64.3
Potassium nitrate	kg	160.4	10.6	0.0	0.0
Irrigation					
Water use	m^3	21.2	12.4	12.2	12.2
Electricity consumption for pumping	kWh	713.0	419.2	499.3	529.2
Plant protection agents (selection of most used)					
Chlorpyrifos	kg	2.2	0.9	1.2	1.0
Methomyl	kg	0.5	0.1	0.2	0.2
Sulphur	g	34.4	7.9	0.0	0.0
Tebuconazole	g	78.9	22.9	15.6	12.5
Outputs					
Products					
Green asparagus	t	1	1	1	1
Emissions to air					
CO_2 (diesel)	kg	39.0	39.5	28.6	22.9
CO_2 (fertilization)	kg	0.0	0.0	49.2	39.4
NH_3 (fertilization)	kg	1.18	0.66	3.07	2.46
N_2O (fertilization)	kg	0.60	0.33	0.01	0.01
NO_x (fertilization)	kg	2.71	1.51	1.81	1.45
Emissions to water					
NO_3 (fertilization)	kg	64.3	36.0	1.6	1.3

Table 3
Summary of the annual inventory data for subsystem II – processing stage (data per functional unit).

	Unit	2010	2011	2012	2013
Inputs from the technosphere					
Polypropylene	g	–	225.0	225.0	225.0
HDPE	g	–	29.70	29.70	29.70
Electricity (storage prior transport)	MJ	–	0.40	0.41	0.42
Electricity (asparagus processing)	MJ	–	0.39	0.39	0.41
Inputs from nature					
Fresh asparagus	kg	–	5.0	5.0	5.0
Outputs					
Asparagus box	p	–	1	1	1

Table 4
Summary of the annual inventory data for subsystem III – distribution stage (data per functional unit).

	Unit	Value
Inputs from the technosphere		
Lorry (to Callao)	km	260
Transoceanic freight – Miami	km	4776
Transoceanic freight – Los Angeles	km	6767
Intercontinental aircraft – London	km	10,149
Intercontinental aircraft – Los Angeles	km	6717
Intercontinental aircraft – Miami	km	4128
Methyl bromide fumigation (US only)	g	1.80
Outputs to the technosphere		
Products		
Asparagus box	p	1
Emissions to air from lorry cooling agents		
HFC-134a	µg	10.47
CFC-12	µg	0.53
HCFC-22	µg	4.71

for use in industrial processes for canning or other non-conventional presentations of green asparagus. On the basis of these conditions a mass allocation perspective was followed since the economic value of some of the co-products was unknown. Consequently, 80% of operational activities from the cultivation site were assigned to the exported product.

The cultivation site is also comprised of 51 ha destined to the production of pomegranates and 6 ha of blueberries. Hence, a series of inputs that were common to the entire production area were allocated based on different criteria. In the first place, in the case of electricity it was determined that water pumping for irrigation was responsible for roughly 98% of electricity consumption. This led to an allocation strategy based on the proportional amount of water used for each crop, which is described in Table 5. Secondly, machinery was in most cases used transversally among the three different crops, as shown in Table 6. However, while in the case of electricity, the water use was obtained in the form of primary data for each crop, in the case of machinery, the company did not have quantified the historic data for each crop. Therefore, the indications in Table 6 correspond to educated estimations by the company's workers, rather than quantified data.

It should also be noted that no harvest was performed in year 2010, since this was the seedling and first year of plantation. Therefore, the impacts of this year of operation were assigned proportionally throughout the estimated duration of the current plantation until a new seedling process is initiated (12 years). In addition, year 2010 includes, as can be observed in Table 7, the inventories of producing and transporting the seeds in California, as well as a nursery stage in Lima.

The irrigation infrastructure, as well as the use of high density polyethylene boxes for harvest, was assumed to be used over a period of 15 years prior to replacement. Therefore, in a similar way as for seedling, the environmental impacts were allocated proportionally throughout the 15 year window.

Finally, the transport of fresh asparagus abroad was modelled based on the export destinations reported by the company. We assumed direct marine or airfreight from Callao to the city of destination, although it should be highlighted that in many cases logistics are more complex, including several intermediate destinations, an issue that could potentially increase the environmental impacts reported in this case study and constitutes a relevant source of uncertainty. For US exports, it is important to note that US customs currently require fresh green asparagus from Peru to be fumigated with methyl bromide. Therefore, based on the fumigation guidelines provided by the Plant Protection and Quarantine (PPQ) division of the United States Department of Agriculture's Animal and Plant Health Inspection Service (USDA APHIS), approximately 1.8 kg of methyl bromide were considered to be fumigated per 28 m^3 of fresh green asparagus (USDA, 2015).

2.6. Life cycle impact assessment and assessment methods

The Life Cycle Impact Assessment (LCIA) stage, in which the material and energy flows are converted into environmental impacts through the use of characterization factors, was computed in the software SimaPro 8.01 (PRè-Product Ecology Consultants, 2014). One single assessment method was selected: ReCiPe midpoint. Midpoint perspectives in LCA quantify the potential impact of a specific environmental dimension (Goedkoop et al., 2009), enabling the identification of key inputs and emissions responsible for environmental impacts, whereas endpoint perspectives quantify the potential damage that a specific impact category, or cluster of categories can pose in terms of human health, ecosystems or resource depletion (Hauschild et al., 2013). While the endpoint perspective is highly useful in terms of public policies, its

Table 5
Allocated electricity values in MWh for the different crops in the cultivation site based on water pumping for irrigation.

Crop	2010		2011		2012		2013	
	Irrigation (m^3/ha)	Electricity (MWh)	Irrigation (m^3/ha)	Electricity (MWh)	Irrigation (m^3/ha)	Electricity (MWh)	Irrigation (m^3/ha)	Electricity (MWh)
Green asparagus	3357	188.19	9685	325.11	8917	301.79	11,719	479.35
Pomegranate	2456	137.69	3967	133.16	5958	201.65	6259	256.02
Blueberries	0	0.00	7524	252.57	6411	216.98	7842	320.77
Total	5813		21,176		21,286		25,820	

Table 6
Machinery allocation per crop (based on educated estimations by site workers).

Crop	2010		2011–2014		
	Green asparagus	Pomegranate	Green asparagus	Pomegranate	Blueberry
Tractor 1 (John Deere)	0.25	0.75	0.25	0.75	0.00
Tractor 2 (John Deere)	0.25	0.75	0.25	0.75	0.00
Tractor 3 (Ferrari)	–	–	0.00	1.00	0.00
Tractor 4 (Massey Ferguson)	0.50	0.50	0.35	0.35	0.30
Straddle tractor (John Deere)	0.80	0.20	0.60	0.10	0.30

uncertainties are rather large. In addition, in this assessment the toxicity impact categories included in ReCiPe were excluded due to the lack of emission factor computation for plant protection agents. Therefore, based on these two limitations, the assessment focused on the midpoint impact categories listed in Table S5 in the SM.

The selection of impact categories was based on an integrated assessment in which the stakeholders were interested in evaluating the widest available number of environmental dimensions. This strategy allows considering trade-offs when interpreting the results and suggesting improvement actions. Nevertheless, the main interests of the stakeholders from a dissemination perspective were climate change and water use. On the one hand, the Peruvian agricultural sector and land use changes linked to its expansion represent a considerable amount of overall national GHG emissions. Given the recent compromise reached at the COP20 summit in Lima (Peru), in which emerging nations committed to develop domestic strategies for GHG emissions reduction (UNFCCC, 2014). In the case of Peru it seems plausible that many of these strategies will be linked to the agricultural sector, given the high potential for GHG-related emissions due to land use changes (Pielke et al., 2002; Wassenaar et al., 2007). On the other hand, water use and management, since water is a key resource in a desert area in which the only existing water source is an aquifer (Prinz, 2002; Budds and Hinojosa-Valencia, 2012).

Table 7
Inventory data per hectare of cultivation for the seedling year (2010).

	Unit	2010
Inputs from the technosphere		
Fossil fuels		
Diesel consumption	kg	20.6
Organic fertilizers		
Guano	t	40.0
Inorganic fertilizers		
Ammonium nitrate	kg	248.2
Phosphoric acid	kg	109.7
Potassium sulphate	kg	106.6
Magnesium sulphate	kg	12.1
Calcium nitrate	kg	11.5
Potassium nitrate	kg	216.4
Irrigation		
Water use	m^3	3357
Electricity consumption for pumping	MWh	1.6
Plant protection agents (selection of most used)		
Imidacloprid	g	84.4
Methomyl	g	540.0
Sulphur	g	19.0
Difenoconazol	g	120.0
Deltamethrin	g	75.0

3. Results

3.1. Environmental assessment of the agricultural phase

Environmental impacts across impact categories were dominated by the production of inorganic (and to some extent organic) fertilizers in most impact categories, especially for metal depletion (66%), ionizing radiation (62%) or ozone depletion (60%), as shown in Fig. 1 (results for year 2013). On field emissions due to fertilization were also an important source of impact in terms of terrestrial acidification (64%), eutrophication, and to a lesser extent particulate matter formation (47%) and photochemical oxidant formation (40%). Therefore, the production, transport and use of fertilizers were identified as the main contributor to environmental impacts in 12 out of 14 impact categories assessed (see Table S5 in the SM), including climate change (CC).

Concerning CC, 47% of the total impacts in the cultivation phase in 2013 were linked directly to fertilization activities (mainly production: 41% of total impacts). Nevertheless, irrigation activities represented 41% of the GHG emissions, of which 16% were directly attributable to electricity use at the site, 13% to the infrastructure beyond the site and 13% to on-site infrastructure. These relative values for CC translate into a total of 4.37 kg of CO_2 eq. per FU in 2013, 11% lower than for 2012 (4.91 kg CO_2 eq.) and 51% for 2011 (8.86 kg CO_2 eq.), but substantially higher for the estimations performed in 2014, 24% (3.53 kg CO_2 eq.) and 2015, 50% (2.92 kg CO_2 eq.).

The main operation responsible for water depletion (WD) was direct irrigation of the fields, representing roughly 63% of the environmental impacts. In addition, electricity production and distribution for water pumping was responsible for an additional 10% of environmental burdens. Despite the elevated irrigation needs in this extremely arid location, 26% of WD was attributable to other uses, such as the production of fertilizers (19%) or machinery (*ca.* 3%).

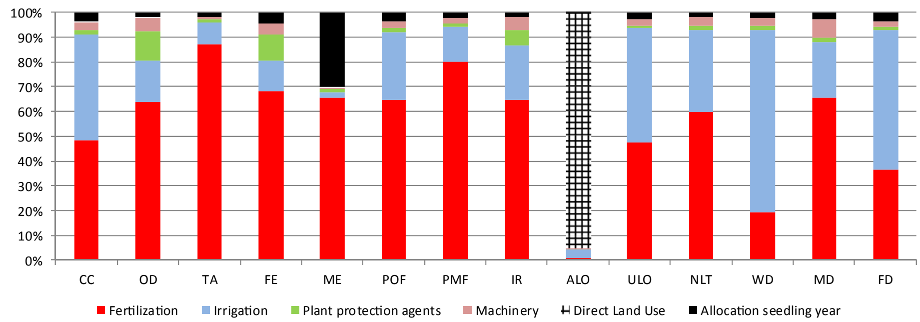

Fig. 1. Relative contribution of operational activities to the environmental profile of the impact categories selected in the agricultural stage (reference year: 2013). NOTE: CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; POF = photochemical oxidant formation; PMF = particulate matter formation; IR = ionizing radiation; ALO = agricultural land occupation; ULO = urban land occupation; NLT = natural land transformation; WD = water depletion; MD = metal depletion; FD = fossil depletion.

Regarding agricultural land occupation (ALO), the main contributor was the total surface destined to the production of the green asparagus (95%), whereas 4% was attributable to irrigation activities and a negligible 1% to the production of fertilizers. Other operational inputs, such as the use of machinery appeared to have surprisingly low impacts considering the use of fossil fuels for their use. In fact, only 11% for ozone depletion, 8% of the impacts of metal depletion and 6% for CC were attributable to mechanical activities on site. Finally, the environmental impacts considered for the seedling year (i.e., 2010), represented impacts below 5% for all impact categories, except for marine eutrophication, that accounted for 30% of total impact due to the increased emission of nitrates and ammonia from the use of inorganic and organic fertilizers.

3.2. *Environmental assessment of the packaging phase*

The packaging phase represented the lowest environmental impacts in all impact categories, due to the lack of complex processing mechanisms in the production system. Therefore, the packaging process of 1 box of asparagus represented the emission of 558 g CO_2 eq. to the atmosphere. The main environmental impact identified in this stage was the production and delivery of plastic materials. On the one hand, environmental impacts ranging from 5% to 11% of the total for this subsystem were identified linked to the use of harvesting boxes (high density polyethylene) at the cultivation site, while the most relevant impacts were attributable to the use of the polypropylene boxes to pack the 5 kg of fresh green asparagus ready for exporting abroad (see Fig. 2). Therefore, 86% of the environmental impacts linked to fossil depletion in this stage and 84% for CC were associated with the supply of the polypropylene box to the packaging plant.

Freighting of the harvested asparagus was considered in this stage up to the packaging point. This truck transport represented up to 55% of the impacts for urban land occupation or 45% for ozone depletion and ALO, whereas contributions were negligible for CC (4%) and fossil depletion (2%). Finally, electricity use in the storage and packaging stages only represented substantial burdens in terms of WD (20%) and natural land transformation (11%).

3.3. *Environmental assessment of the distribution stage*

The distribution stage was considered from the gate of the packaging centre. Therefore, two were the main operations taken into account: transportation by truck to the port of Callao and exportation abroad. However, exports were highly conditioned depending on the freight mode and distance. In other words, when green asparagus is exported by boat to Miami (US), the environmental impacts of road transportation in Peru represent 62% of impacts within this subsystem for metal depletion, 31% for FD and 28% for CC, whereas marine freighting to Miami represented up to 88% of the impacts in particulate matter formation or 72% in the case of CC (see Fig. 4). Interestingly, ozone depletion impacts were identified as being crucial in this stage whenever the exported products enter US customs for commercialization. The reason behind this circumstance is linked to the fumigation process that occurs at customs, representing 99.9% of total environmental

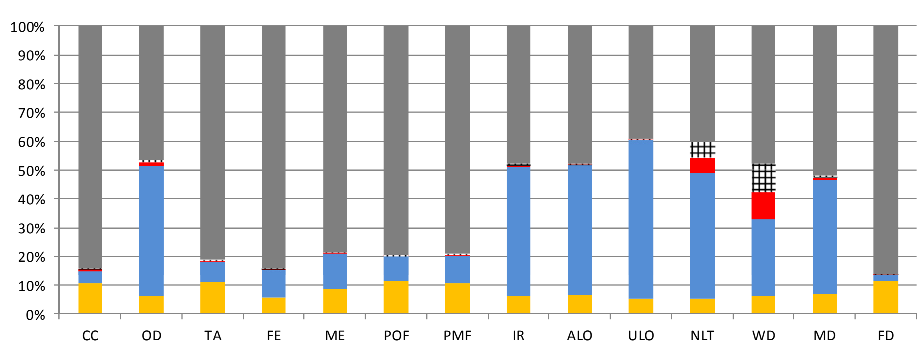

Fig. 2. Relative contribution of operational activities to the environmental profile of the impact categories selected in the packaging stage (reference year: 2013). NOTE: CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; POF = photochemical oxidant formation; PMF = particulate matter formation; IR = ionizing radiation; ALO = agricultural land occupation; ULO = urban land occupation; NLT = natural land transformation; WD = water depletion; MD = metal depletion; FD = fossil depletion.

impacts. However, it is interesting to point out that when the cargo is airfreighted to London (UK), and therefore no fumigation with methyl bromide is necessary on arrival, the environmental impacts of intercontinental freighting represent at least 90% of the environmental load for all impacts categories (Fig. 3).

3.4. Overall environmental profile of asparagus

The overall environmental profile of asparagus production showed a gradual improvement from the first harvest in 2011 to the fourth harvest in 2014, which to a great extent can be linked to the asparagus yield curve, as can be observed in Fig. 4. For instance, the GHG emissions in the CC impact category decreased from 29.0 kg CO_2 eq in 2011 to 19.9 kg CO_2 eq in 2014. In addition, Fig. 4 also shows the estimated GHG emissions for future years of production based on the producers estimates regarding the yield curve for asparagus, and maintaining the same energy and material flows as in year 2014. Hence, in 2015 considering the same technology and operational inputs as in 2014, as well as reaching a peak yield value of 12.0 t/ha, the CC impacts would add up to 16.6 kg CO_2 eq. Finally, the evolution through time of the environmental impacts in selected categories is depicted. While in most impact categories the burdens per FU tend to decrease with increasing yields, this was not the case for ozone depletion given that the most hazardous compounds for the ozone layer are emitted in the distribution subsystem. However, the fact that impacts per FU in years 2012 and 2013 were remarkably similar, despite an increase in green asparagus yield of 33%, was linked mainly to the change in fertilization practices, due to the use of urea rather than ammonium nitrate. This change is most visible for the particulate matter formation category, since NH_3 and NO_x (emissions of NH_3 and NO_x were considerably higher in 2013 as compared to 2012 – see Table 2) have a relatively high characterization factor in this impact category (Goedkoop et al., 2009).

Nevertheless, it should be taken into account that the overall life-cycle results presented above consider a weighted average of the export routes from Peru to the two importing nations. When the different exporting routes are independently assessed, the differences are noticeable when discriminating between marine and airfreighting, as can be seen in Fig. 5. Consequently, the

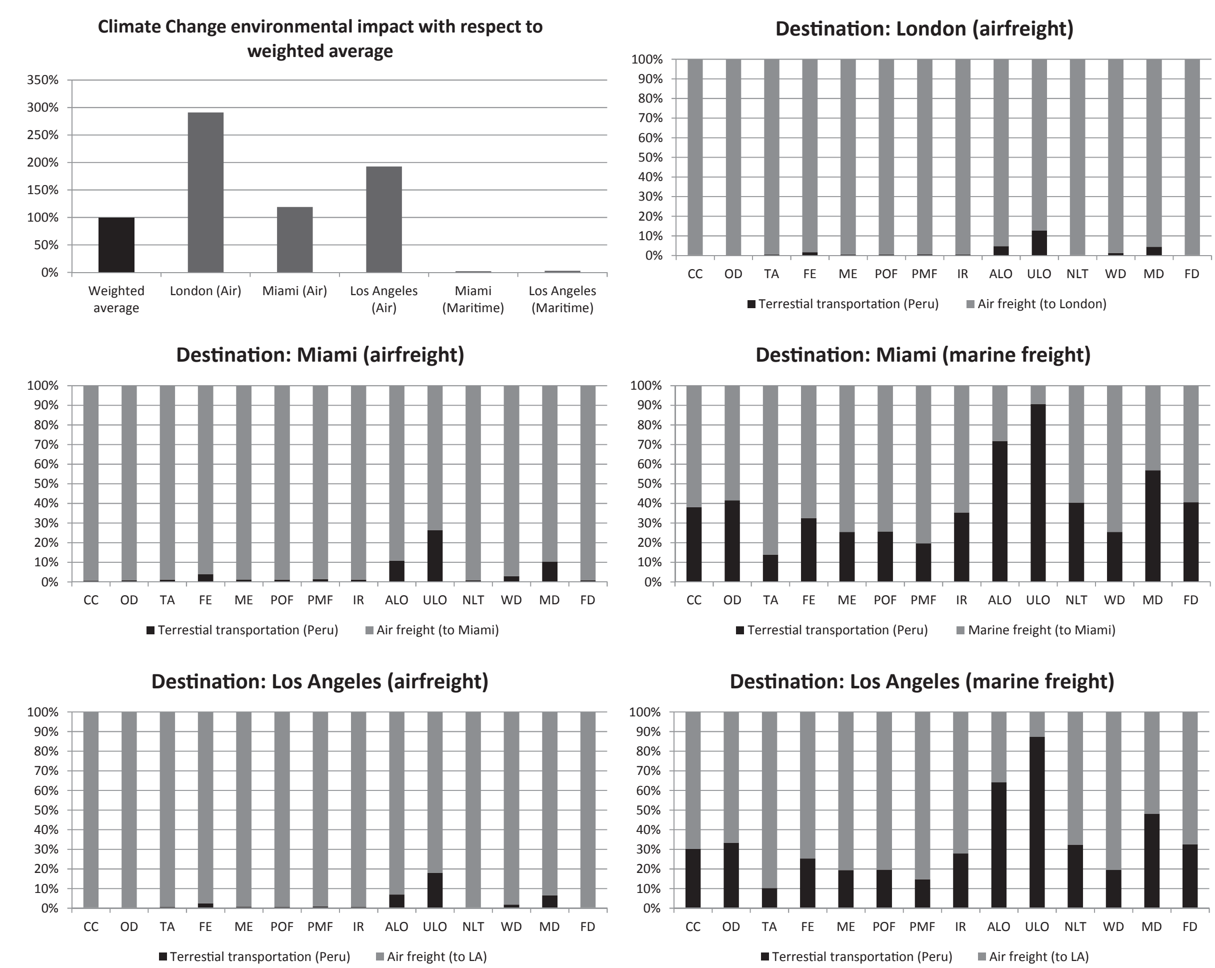

Fig. 3. Graphical representation of the comparison between weighted average destinations and individual destinations in terms of GHG emissions for the distribution stage. Relative contribution of operational activities to the environmental profile of the impact categories selected in the distribution stage, including transoceanic freighting (air and maritime) to final destination (reference year for all graphs: 2013). NOTE: fugitive emissions due to fumigation at US customs were excluded; CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; POF = photochemical oxidant formation; PMF = particulate matter formation; IR = ionizing radiation; ALO = agricultural land occupation; ULO = urban land occupation; NLT = natural land transformation; WD = water depletion; MD = metal depletion; FD = fossil depletion.

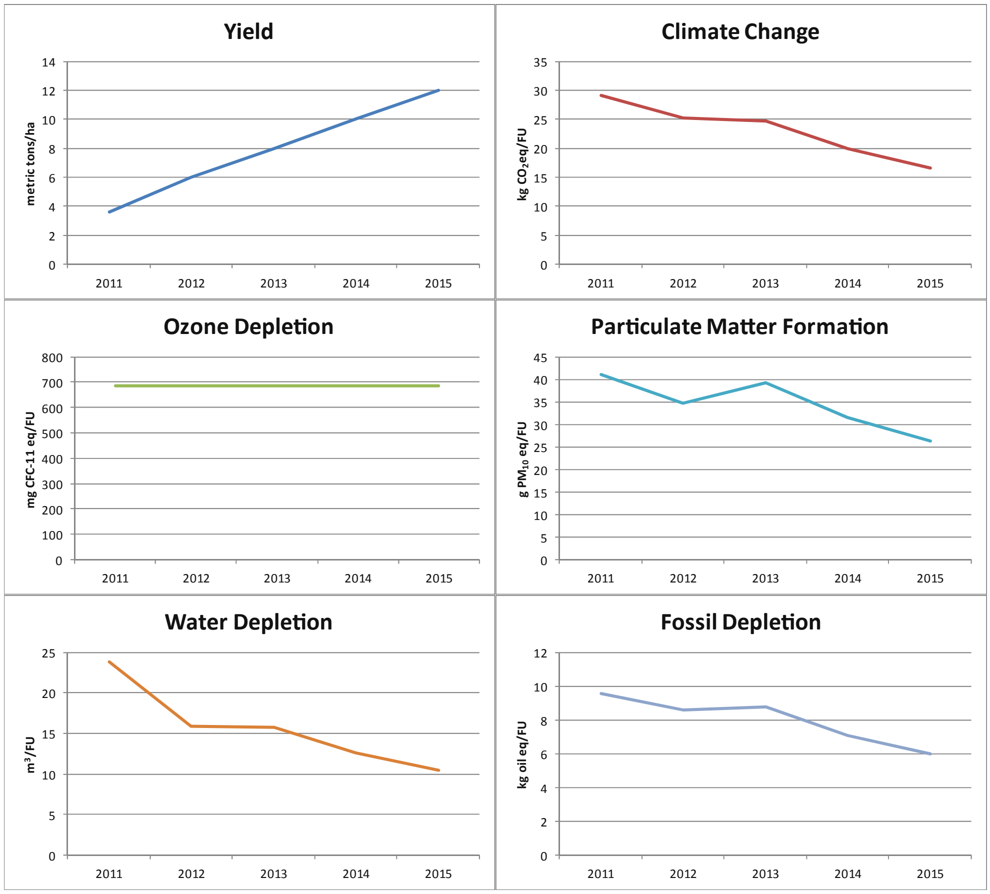

Fig. 4. Total environmental impacts for selected impact categories in the period 2011–2015 per functional unit (5 kg box of green asparagus), as well as average yield (tonnes per hectare) in the analyzed period.

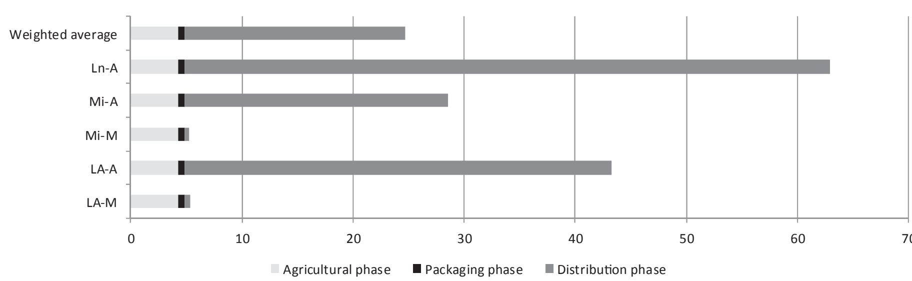

Fig. 5. Total environmental impacts for the climate change (CC) impact category in 2013 depending on the final destination and transport mode. Weighted average for all five scenarios is also provided. Results are expressed in kg CO_2 eq. per functional unit (5 kg box of green asparagus). NOTE: Ln-A = airfreight to London; Mi-A = airfreight to Miami; Mi-M = marine freight to Miami; LA-A = airfreight to Los Angeles; LA-M = marine freight to Los Angeles.

shipment of a box of fresh green asparagus to the US by sea can show environmental impacts up to 92% lower than airfreighting them to the UK.

4. Discussion

4.1. Environmental hotspots and improvement actions

The main environmental hotspots identified in the production and supply chain of green asparagus production for this company were linked mainly to the production of raw material outside Peruvian borders. In fact, it is somewhat stunning to find that a nation that destines 33,000 km^2 to agricultural production has to import close to 100% of key raw materials in the industry, such as inorganic fertilizers or plant protection agents (INEI, 2014b). Therefore, in many cases the environmental profile of Peruvian agricultural products will be penalized by the use of inorganic fertilizers produced in countries such as Belgium, China or Russia (Ministerio de Agricultura, 2011, 2012, 2013). Beyond the environmental impacts linked to freighting these products, which are not excessive since the freight is mostly maritime and slow, the production of inorganic fertilizers is highly energy intensive. This circumstance is aggravated by the fact that Peru imports some of these products from nations (e.g., China or Russia) whose electricity mix is still based to a great extent on fossil fuels. Consequently, beyond the actual decision-making that can be displayed at a company level, it would be desirable that public policies in Peru, taking advantage of the beneficial position of the country in terms of access to many raw materials and low carbon electricity production (Vázquez-Rowe et al., 2015), were driven to close the production cycle of resources used in the agricultural sector, such as plant protection agents or inorganic fertilizers.

In addition to this important constraint that affects most agricultural products in Peru, changes in the energy matrix in Peru are also expected to imply future changes in the environmental impacts of this type of products. For instance, the electricity grid in Peru, while strongly based on hydroelectric power, has steadily changed to meet increasing electricity demands (Vázquez-Rowe et al., 2015). This has created a situation in which the additional demand of electricity production has been supplied by the use of fossil fuels, although the investments planned for the period 2015–2018 suggest that this situation would shift to an integrated use of different energy sources, including wind, solar and new hydropower installations (OSEC, 2010; UK Trade & Investment, 2010). Similarly, the expected development of new infrastructure in the Ica region in the period 2015–2020, with the opening of a new international port at the city of Pisco (13°42′36″S; 76°12′12″W), would reduce considerably the terrestrial freighting within Peruvian borders of raw materials and final products ready for exportation, since these would not be centralized any longer in the port of Callao.

In fact, a scenario for green asparagus production in 2013 was modelled based on changes in freight distances, assuming a *ceteris paribus* situation for all other practices in terms of operational inputs. The results, which are visible in Table 8, demonstrate that the opening of an international port in Pisco would imply a slight reduction in environmental impacts: 6% for urban land occupation, 4% for ionizing radiation or 2% for CC, assuming that the cargo was marine-freighted to Los Angeles (US). In addition, this infrastructure would reduce considerably the amount of agricultural cargo being transported to Lima–Callao along the Pan-American Highway through the most densely-populated area of the country (APN, 2015). Besides the environmental impacts of green asparagus production modelled in this scenario, and despite it being beyond the scope of this study, it is worth mentioning that the development of this type of infrastructure in the Ica region would probably be accompanied by a proliferation of land use changes (LUCs) in the area in terms of agricultural land expansion due to the lower freight costs.

From a company level the main observations in the timeframe analyzed can be linked to two main factors. On the one hand, increasing yield from the first year of production onwards had an important effect on lowering the environmental profile of green asparagus. Surprisingly, when consulting the LCA literature available for this type of crops, there is little reference to the effect of the yield curve on the environmental impacts, and in a majority of studies the environmental data are referred to one single year of operation without any reference to the stage of development of the permanent crop (Vázquez-Rowe et al., 2012). Therefore, it would be desirable that future studies in the agricultural sector were more explicit when reporting environmental results, since the yield curve of permanent crops, as well as other temporal factors, can have an important influence on these. In other words, as observed previously by Brentrup (2003), perennial crop systems tend to show a non-monotonic curve due to the fact that the systems are predominantly output-oriented, since many inputs respond to cycles that go beyond the annual harvest. This relationship, as represented in Fig. 6, tends to translate into a U-shaped curve, in which the lowest environmental impacts are attained once the crops achieve the highest level of yield per unit of land (Brentrup et al., 2004). Furthermore, it should be noted that the identification of the life-cycle impact of decreasing yields due to the end of peak yield performance by perennial crops may be a way forward to better understand when farmers should replace their crops to maintain low impacts at high yields. Finally, it should be noted that the described behaviour contrasts with that of annual crops (e.g., cereals, corn, etc.), which tend to be more prone to annually-based inputs, such as nitrogen fertilization.

When analyzing in depth some of the impact categories assessed, it is important to highlight how different activities have an uneven effect on the final environmental profile. For instance, ozone depletion impacts showed a very high prevalence of the distribution stage due to a legal requirement of the Plant Protection and Quarantine (PPQ) service of the US Department of Agriculture at US customs to use methyl bromide fumigation for a series of agricultural products, including most vegetables such as asparagus (Baca, 2014). In fact, in 2013 a total of 545,000 lbs of methyl bromide were used by the US for import fumigations. Approximately 15% of this fumigation was attributable to asparagus (Baca, 2014). Its use is justified on the basis that it is an effective chemical to prevent agricultural products from propagating invasive plant pests or noxious weeds. Interestingly, methyl bromide presents a relatively high characterization factor for ozone depletion (characterization factor – CF = 0.38), although lower than CFC-11 (CF = 1) (ReCiPe, 2015). While its use other than for fumigation purposes has been cut by approximately 82% in the period 1995–2012, in

Table 8
Environmental impacts per functional unit in 2013 assuming current conditions as compared to the export of green asparagus from the projected port of Pisco. Results are expressed per functional unit (5 kg box of green asparagus). Both systems consider that the green asparagus is exported through marine freight to the US.

Impact category	Unit	2013		% Improvement
		Current system	Production system assuming that the port of Pisco was already in operation	
Climate change	kg CO_2 eq.	5.34	5.25	1.70
Ozone depletion	mg CFC-11 eq.	685.3	685.3	0.00
Terrestrial acidification	g SO_2 eq.	76.13	76.01	0.16
Freshwater eutrophication	g P eq.	1.08	1.06	1.38
Marine eutrophication	g N eq.	6.88	6.87	0.16
Photochemical oxidant formation	g NMVOC	31.11	30.78	1.05
Particulate matter formation	g PM_{10} eq.	17.96	17.81	0.82
Ionizing radiation	kBq 235 eq.	0.256	0.246	3.91
Agricultural land occupation	m^2 a	6.60	6.59	0.06
Urban land occupation	m^2 a	0.221	0.208	6.21
Natural land transformation	m^2	9.64E−4	9.35E−4	2.95
Water depletion	m^3	13.15	13.05	0.74
Metal depletion	kg Fe eq.	0.286	0.275	3.84
Fossil depletion	kg oil eq.	2.25	2.22	1.50

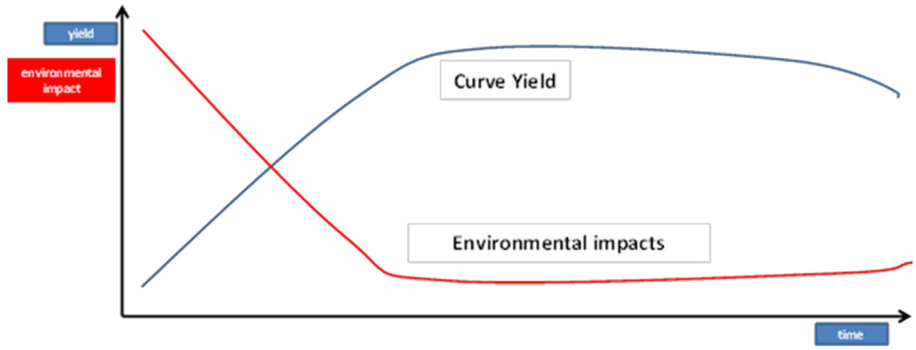

Fig. 6. Graphical representation of the relationship between the yield curve and environmental impacts per functional unit through the life cycle of green asparagus cultivation.

2012 the use of methyl bromide for quarantine and pre-shipment (QPS) in the US represented over 60% of global emissions of this substance.

Nevertheless, the Montreal Protocol exempts QPS activities from the phase-out of this chemical, although certain nations are starting to demand that the QPS exemption should be revised (Butler and Montzka, 2014), although the PPQ and the Environmental Protection Agency (EPA) in the US are already working on implementing alternative feasible procedures. For example, the use of phosphine, which has no effect on the ozone layer, has been tested positively for different crops including asparagus (Liu, 2008), although its high human toxicity potential implies that further research should be performed in terms of phosphine residues in these products to avoid risks to human health (Brautbar and Howard, 2002; Liu, 2008). Another option suggested by the UNEP in a recent report in 2014 is the use of sulfuryl fluoride (SO_2F_2). This chemical has no effect on ozone depletion, but poses an important problem in terms of global warming potential (GWP). In fact, its environmental impact is yet to be included in the IPCC characterization factors for direct GHGs, although some studies suggest that its characterization factor could be as high as 8000 (Dillon et al., 2008). Therefore, although the two alternatives presented imply a complete eradication of ozone depletion impacts in the fumigation phase, their trade-offs in other environmental dimensions, such as CC or toxicity, may be an important issue of concern.

Another impact category of interest, particulate matter formation (PMF), was found to be driven by particles emitted in the spreading of fertilizing agents (47% in 2013). Therefore, seeking certain equilibrium between agronomic choices to boost productivity and the environmental impacts that different fertilizing agents engender may provide a successful management strategy to reduce environmental impacts. Nevertheless, it should be noted that the site is located in a low population density area, which implies that the importance of PMF may not be as relevant as in other areas along the Peruvian coast. In addition, other impact categories, such as marine eutrophication or terrestrial acidification, would also benefit from this management strategy.

The use of water is always a controversial issue in hyper-arid areas of the planet like this region in Peru. However, at the cultivation site a High Frequency Intermittent Drip Irrigation System (HFDI System) has been in operation ever since the first year of operation in order to minimize water use (approximately 45%), as well as associated energy (45%) and fertilizer use, such as ammonium nitrate (52%), potassium sulphate (50%) or phosphoric acid (10%). This infrastructure implies that the average direct water use per hectare in this cultivation site is below 11,800 m^3/ha/year, substantially lower than the 14,000–17,000 m^3/ha/year reported as industry benchmark in the area (Hepworth et al., 2010). These important savings in water use imply a lower impact on the already overexploited aquifers in the region of Ica (World Bank, 2008), as well as substantial improvements in terms of eutrophication potential due to lower fertilizer use or lower electricity use, as can be observed in Table 9. This table compares the performance of on-site asparagus production using the HFDI system to the conventional flood irrigation system used in most of the Ica Valley. Results show that disregarding ALO, all other impact categories have improved performance of 40–50% when the HFDI system used at the cultivation site rather than the regional benchmark.

All these advantages linked to the HDFI system confirm the statements that were previously suggested regarding the good performance of operational activities at the cultivation site. The difficulty to further reduce water consumption on site, therefore, redound in the struggle to further benchmark electricity and fertilizer use at the agricultural site. Therefore, improvement actions in a wide range of environmental impact categories will be linked more to the outsourced impacts linked to the production of the energy and material flows needed at the site, rather than on the actual way in which operational activities are performed locally.

Finally, regarding the use of plant protection agents, it should be noted that in March 2015 the World Health Organization (WHO), through its International Agency for Research on Cancer (IARC), has classified the herbicide glyphosate as probably carcinogenic to humans (IARC, 2015). Glyphosate is the most used organophosphorus herbicide worldwide, although the cultivation site analyzed only used this product in the 2012 campaign. Therefore, based on the low reliance on glyphosate, it is feasible to state that this cultivation site should not suffer the potential phase out of this herbicide.

4.2. Comparison with other asparagus production systems

Several studies have delved into analyzing the life-cycle of green asparagus production and processing, although to the best of our knowledge most of these were limited to the quantification of the GHG emissions (Bartl et al., 2012; Stoessel et al., 2012; Zafiriou et al., 2012). For instance, Soode et al. (2015) performed the carbon footprint of green asparagus cultivation in Germany. The results, while in line with those obtained in the current study in terms of the cultivation phase, were slightly higher in terms of GHG emissions due to the existence of a heating system for the soil where these green asparagus were cultivated. A similar study was conducted by Morgan et al. (2007) for green asparagus consumption in Seattle. More specifically, they compared the production and freight of green asparagus from two different locations: Yakima (WA, US) and Ica (Peru). While the authors admit that some vague assumptions were made in terms of diesel and fertilizer use in the cultivation of green asparagus, they point out that marine freighted asparagus from Peru emits a considerably lower amount of GHG

Table 9
Environmental impacts per functional unit in 2013 comparing the High Frequency Intermittent Drip Irrigation System (HFDI) to conventional drip irrigation. Results are expressed per functional unit (5 kg box of green asparagus). Both systems consider only the agricultural stage up to the gate of the farm.

Impact category	Unit	2013		% Improvement
		HFDI	Flood irrigation	
Climate change	kg CO_2 eq.	4.25	7.13	40.41
Ozone depletion	mg CFC-11 eq.	13.78	25.09	45.07
Terrestrial acidification	g SO_2 eq.	66.22	132.00	49.83
Freshwater eutrophication	g P eq.	0.99	1.84	46.08
Marine eutrophication	g N eq.	6.59	11.26	41.47
Photochemical oxidant formation	g NMVOC	22.07	38.67	42.93
Particulate matter formation	g PM_{10} eq.	14.63	28.33	48.37
Ionizing radiation	kBq 235 eq.	0.199	0.379	47.54
Agricultural land occupation	m^2 a	6.59	6.91	4.59
Urban land occupation	m^2 a	0.20	0.40	49.84
Natural land transformation	m^2	7.97E−4	1.56E−3	48.77
Water depletion	m^3	12.53	24.58	49.04
Metal depletion	kg Fe eq.	0.26	0.51	48.58
Fossil depletion	kg oil eq.	1.66	2.42	31.36

emissions in the cultivation phase (approximately 50% less). However, these lower emissions are then neutralized due to the fact that the distance to transport asparagus from Peru to Seattle is considerably larger than from Washington State, even though marine freight is less intensive in terms of emissions than transport with light trucks. Having said this, it should be noted that the season for green asparagus production in Washington states spans from April to June (Sun et al., 2007), whereas the climatic conditions in Peru allow harvesting throughout the year. Therefore, competition between fresh asparagus from either destination only occurs on a seasonal basis.

A report conducted by ClimaTop (2009) compared asparagus from different parts of the world being consumed in Switzerland. The results presented a similar scenario to that depicted in the current study: GHG emissions relating to asparagus produced in Peru, Hungary or Germany presented a similar range as long as they were not airfreighted to Switzerland, whereas a strong correlation between airfreighted distance and final carbon footprint value was observed for Peruvian (12.2 kg CO_2 eq./kg of asparagus) and Mexican asparagus (10.8 kg CO_2/kg).

Nevertheless, despite this resembling trend, the results in the current study demonstrate that the final GHG emissions reported per unit of mass in the production of green asparagus in Peru appear to be substantially lower than those reported in the literature, provided that the years of peak yield are considered in the assessment. Therefore, for the case of green asparagus it appears evident, at least when analyzing the GHG emissions, that the concept of food miles can be extremely deceiving, since the main emissions linked to transport are going to depend on the type of freight (Webber and Matthews, 2009). Hence, exporting green asparagus by ship to the US appears to compete with the production of locally-grown asparagus in the US.

Regarding airfreighting, it should be noted that producers on average have approximately 28 shelf days for fresh green asparagus to arrive to the consumer's refrigerator. While this allows Peruvian companies to export asparagus by ship to North America, this is not the case for Europe, where all the cargo is airfreighted. Consequently, the development of technology that would allow a longer lifespan for green asparagus would most likely allow considerable reductions in environmental impacts in the distribution stage. Nevertheless, it should also be considered that green asparagus cultivation in Peru allows considerably higher yields than their production in European nations. Hence, it seems plausible that land in European countries may be more appropriate for other crops rather than green asparagus, especially considering that additional cropland in Peru for green asparagus does not imply deforestation or any other land use change that translates into liberation of biogenic carbon into the atmosphere (Meyfroidt et al., 2010).

Unfortunately, as abovementioned, it was not possible to compare other impact categories since these have not been previously assessed in the literature for green asparagus. Consequently, the assessment of numerous impact categories, as well as understanding the trade-offs between them reinforces the novelty of the present case study.

5. Conclusions and perspectives

This study has calculated the environmental impacts of exporting, to the UK and the US, green asparagus produced in Peru. Given that the results presented correspond to one single company, these do not intend to represent the state-of-the-art of asparagus production in Peru. Having said this, the completeness and depth of the inventory, as well as the relevance of the results may be of utility in terms of benchmarking purposes for other green asparagus producers and wholesalers across the nation. Policy-makers in Peru may also find these results of interest in the constant effort to maintain export products in an increasingly environmentally-friendly demanding sector competitive in northern hemisphere markets.

Previous studies had focused mainly on identifying the GHG emissions linked to the life-cycle of green asparagus production and distribution. However, the results presented in this study have highlighted additional environmental impacts that should be taken into consideration when assessing this agricultural product, delving into how the system process can be improved in terms of cleaner production. Consequently, the importance of minimizing the use of water or attaining an environmentally-friendly balance of fertilizing agents were identified as key issues to be considered at the cultivation site. Nevertheless, an interesting aspect that was also highlighted was the reliance of the Peruvian agricultural sector on imports of fertilizing and plant protection agents, implying that agricultural production systems depend to a great extent on the energy matrix of foreign nations. In contrast, this issue is minimized thanks to the relatively clean domestic electricity production system. Finally, improvements in food technology to extend the shelf time of green asparagus would be a desirable short-term target to allow a lower dependence of airfreighting to final consumption destinations.

An additional aspect presented in this study was the influence of the yield curve on the environmental profile of the product assessed. While this has shown to be an important source of variability in terms of environmental impact on a year to year basis in this perennial crop, it also appears to be an issue that is repeatedly ignored in case studies analyzing perennial crops. Finally, a future line of study in this production system for Peru would be to evaluate the dynamic changes that the expansion of these crops is generating throughout the Peruvian hyper-arid coastal, since many of the cultivations sites have been gained from land that had no previous use or vegetation cover.

Acknowledgements

The authors also thank Minela Chávarri, Juan Pablo Bentín and SwissContact for valuable scientific support. Dr. Ian Vázquez-Rowe wishes to thank the Galician Government for financial support (I2C postdoctoral student grants programme). Authors with affiliation to the University of Santiago de Compostela (Spain) belong to the Galician Competitive Research Group GRC 2013-032.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.09.076.

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