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Environmental and productive performance of different blueberry (V*accinium corymbosum* L.) production regimes: Conventional, organic, and agroecological

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ABSTRACT

Certified organic agriculture stipulates a set of principles and standards which run farmer practices. The current global demand for organic food has raised new challenges for organic agriculture, which can be difficult to address when management is subject to the forces of conventionalisation. Using production of highbush blueberry (V*accinium corymbosum* L.) as a target crop, we analyze environmental impacts comparing three different types of management in south-central Chile: conventional orchards (CO), orchards with organic management based on input substitution (OI), and orchards with organic management based on agroecological principles (OA). We compare these production systems from an environmental and economical perspective using four blueberry orchards for each type of management. Impacts in global warming (referred to as greenhouse gas emissions), acidification, and freshwater eutrophication were estimated using Life Cycle Analysis. Production costs and fruit yields were also quantified for each orchard studied. Blueberry yields were not different among farming systems, although OA achieved the highest one (8.47 ton/ha), with the lowest both cost of production (2265 US $/ha yr.). All environmental impacts were higher for CO. Overall, OA turned out as the most efficient production systems both from an environmental and economic perspective.

1. Introduction

Agriculture and land use change contribute to approx. ¼ of the global greenhouse gas emissions (GHG) (Smith et al., 2014) but these emissions can vary substantially depending on the agricultural practices involved (Snyder et al., 2009). Conventional agricultural production based on external inputs, e.g., synthetic fertilizers and pesticides, has resulted in significant increases in productivity, but simultaneously in higher environmental pressure (Bruinsma, 2017). External inputs and mechanization demand more energy causing higher GHG emissions (Gan et al., 2011). The production and transport of inputs and capital goods towards and from farms is also an important source of indirect CO_2 emissions (Dalgaard et al., 2001; Ahmad and Wyckoff, 2003). In the current scenario of increasing concern regarding environmental effects of food production systems, organic agriculture is considered an environmentally friendly alternative to conventional agriculture (Stolze et al., 2000; Pimentel et al., 2005). However, within organic agriculture it is possible to find different levels of environmental impacts, depending on the agricultural practices involved (Altieri et al., 2017). External inputs for organic agriculture are non-synthetic origin, which makes them more environmentally friendly. But their production and/or application can still have detrimental environmental effects (Eggleston et al., 2006). In addition, mechanization demands energy, having an impact in terms of CO_2 emissions as well (Smith et al., 2014).

The increase in production and consumption of organic food is one of the major market trends of our time (Hughner et al., 2007; Willer et al., 2018), partly because organic farming is perceived by consumers as more sustainable than conventional (Pimentel et al., 2005; Reganold and Wachter, 2016). Supporters of organic agriculture claim that it will help preserve the environment, decrease GHG emissions, improve people's health, and create better conditions for agricultural workers (Lee and Yun, 2015). However, several studies have shown that some certified organic farms do not fulfill these expectations (e.g., Allen and Kovach, 2000; Darnhofer et al., 2010). Their practices comply with the regulations from certification companies, but not with the principles of organic farming, resulting in organic systems that reproduce

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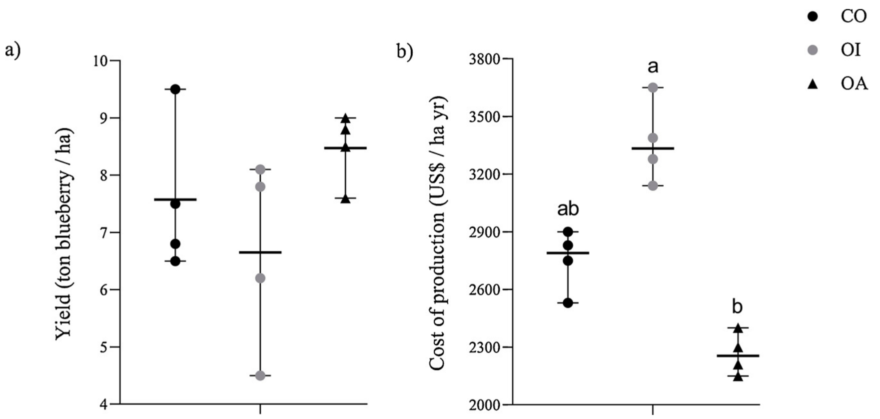

Fig. 1. (a) Blueberry yield, and (b) cost of production for conventional orchards (CO), orchards with organic management based on input substitution (OI), and orchards with organic management based on agroecological principles (OA). The value for each sampled orchard is indicated with a symbol, and horizontal lines represent mean values ± SD. Significant differences (Wilcoxon signed-rank test, BH corrected $p < 0.05$) are denoted by different letters.

Table 1
Inventory of main agricultural inputs (per functional unit) gathered in blueberry conventional orchards (CO), orchards with organic management based on input substitution (OI), and orchards with organic management based on agroecological principles (OA). Values are means ± SD in parenthesis.

	Input	*Unit*	*CO*	*OI*	*OA*
Soil management	Urea nitrogen	kg	42.75 (6.26)	–	–
Synthetic fertilizers	Others N-fertilizers	kg	5.9	–	–
	Lime	kg	8.1	0.18 (0.28)	–
	Potassium fertilizer	kg	12.57 (7.81)	–	–
	Phosphorus fertilizer	kg	16.22 (5.65)	–	–
	Magnesium	kg	3.4 (1.41)	–	–
	Boron	kg	2.1	–	–
Organic fertilizers	Lupine flour	kg	–	145	107 (8.21)
	Nitroamin (hydrolyzed proteins)	kg	–	47.2 (19)	–
	Phosphate Rock	kg	–	439.2 (77.21)	–
	Compost	kg	–	1010.33 (694.22)	297.97 (68.02)
	Fish bones	kg	–	7.15 (1.34)	73.35 (49.04)
Pest control	Copper-based pesticide	kg	0.27 (0.21)	0.2 (0.001)	0.1
	Dimethylamine	kg	0.3 (0.14)	–	–
	Glyphosate	kg	1.52 (0.44)	–	–
	Other herbicides	kg	0.8	–	–
	Pendimethalin	kg	0.25 (0.07)	–	–
	Carbofuran	kg	0.3	–	–
	Fungicidal	kg	0.3 (0.1)	–	–
	Insecticide	kg	0.53 (0.29)	–	–
Machinery	Diesel	kg	10.25 (8.7)	9.32 (2.12)	7.57 (1.15)
	Gasoline	kg	–	16.3	–
Irrigation	Electricity	MJ	182.02 (58.52)	154.25 (30.09)	163.37 (21.68)

management patterns from conventional agriculture, along with their environmental impacts (Oelofse et al., 2011). This trend has been called '*conventionalisation*' of organic farming (De Wit and Verhoog, 2007). According to this, organic farming could thus be subjected to 'industrialization', i.e., the implementation of economies of scale at the farm level, increased dependence on purchased non-farm inputs (machinery, fertilizers, feed, agrichemicals), resource substitution (capital for land and labour), and mechanization of the production process (De Wit and Verhoog, 2007; Guptill et al., 2017). These mechanisms have been observed both at the farm level as well as in the processing and marketing of organic food (Guthman, 2004; Darnhofer et al., 2010).

Organic production practices have also been criticized as inefficient relative to conventional production technologies due to lower yields (Nieberg and Offermann, 2000), even though some large-scale reviews examining comparative yields in conventional and organic agriculture strongly challenge this critique (Badgley et al., 2007). Improving the sustainability of agricultural production systems requires the promotion of farm practices that provide high-quality, affordable food while minimizing negative environmental effects. Food costs (at the farm gate) depend both on production yields (kg/ha) and on production costs, while environmental effects can be assessed using a Life Cycle Assessment (LCA). This method is widely accepted for assessing environmental impacts of processes and products. LCA is an ISO-standardized biophysical accounting framework used to inventory the material and energy inputs and emissions associated with each stage of a product life cycle and to express these in terms of their quantitative contributions to a specified suite of environmental impact categories (Guinée et al., 2001). Such analyses facilitate the identification of lifecycle stages that contribute disproportionately to specific areas of environmental concern, as well as comparisons of environmental performance between competing production technologies.

In this study we analyzed the performance of different agricultural management regimes both from an environmental perspective using LCA, and from a productive economic viewpoint. We based our study on highbush blueberries (*Vaccinium corymbosum* L.) due to its increasing interest in our country, Chile. Worldwide blueberry production has been an increasing trend over the last few years, and Chile is the largest blueberry producer in the southern hemisphere and the second largest worldwide after the USA (Chilean Blueberry Committee 2019).

2. Materials and methods

2.1. Study site

We studied commercial orchards of highbush blueberry located in Region Ñuble (37°20′S, 72°40′E), south-central Chile. This region is the second largest in terms of cultivated area of blueberries in the country with 3428 ha (ODEPA, 2019). In this area, the climate is Mediterranean

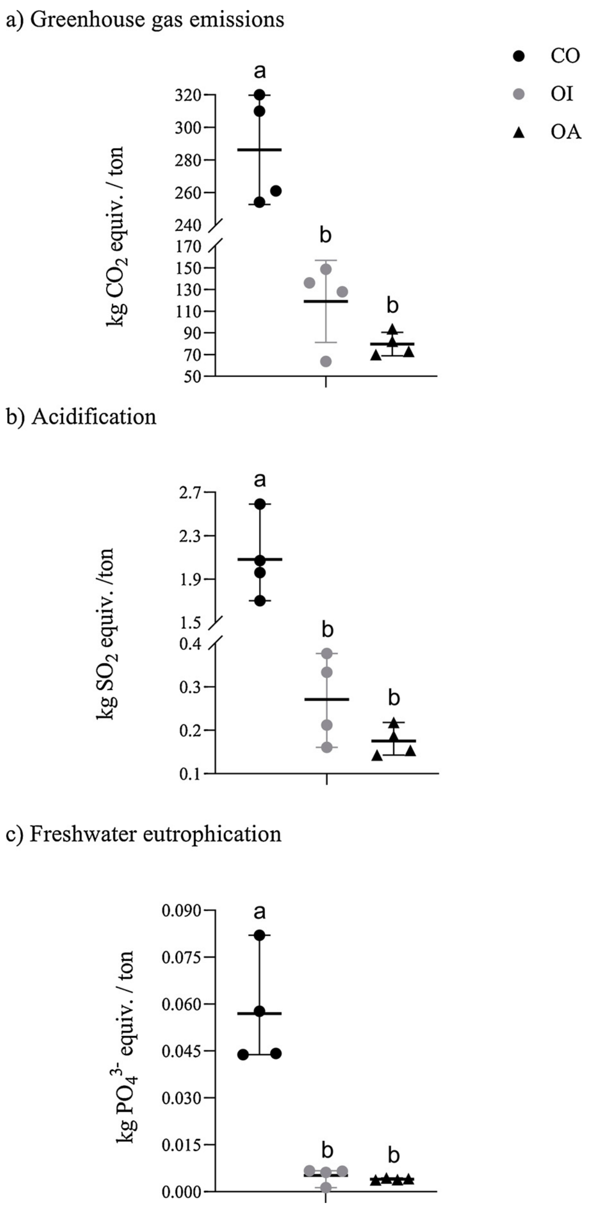

Fig. 2. (a) Greenhouse gas emissions, (b) acidification, and (c) freshwater eutrophication for the production on 1 ton of fresh blueberry in conventional orchards (CO), orchards with organic management based on input substitution (OI), and orchards with organic management based on agroecological principles (OA). The value for each sampled orchard is indicated with a symbol, and horizontal lines represent mean values ± SD. Significant differences (Wilcoxon signed-rank test, BH corrected $p < 0.05$) are denoted by different letters.

with a mean annual precipitation of 1200 mm with 70% falling between May-August, with a dry period of 4–5 months starting in October, and with 5–6 frost-free months (Pozo and Canto, 2015). Mean annual temperature is 13.9 °C with an average temperature of 3.6 °C in the coldest month (June) and 28 °C in the warmest month (January) (Pozo and Canto, 2015). Soils in this area are mostly influenced by volcanic activity, moderate permeability and drainage, and rapid run off (Soil Survey Manual, 2017).

2.2. Sampled farms

The study was conducted in 2015. We restricted our sampled farms to highbush blueberry 'Legacy' orchards with 5 year old plants. We surveyed 35 blueberry orchards and selected four orchards per management regime. Our criteria for this selection was based on data availability and reliability; even though four orchards is a relatively low number, we consider that it should suffice to represent the patterns of each management regime in our results. Management regimes consist in conventional orchards (CO), orchards with organic management based on input substitution (OI), and orchards with organic management based on agroecological principles (OA). CO had no restrictions to the use of synthetic fertilizers and pesticides, only complying current legislation in Chilean environmental policies. Organic farms (OI and OA) were all under organic certification by international certifiers (e.g., BCS-Germany or IMO-Switzerland) and thus had no synthetic inputs. OI used natural fertilizers such as commercial fishmeal or egg-producing poultry (Fernandez-Salvador et al., 2015). OA were managed by a collaboration program between Hortifrut S.A. and Universidad de La Frontera (Chile). The program goal was to produce organic blueberries by maximizing the functional ecological relationships in the agroecosystem (e.g., nutrients solubilization, competition, synergetic relationship, pollination, etc.) with minimal external inputs, especially the ones with high solubility and biocides, even those approved by organic certification (Montalba et al., 2010; Nicholls et al., 2016).

Orchards area ranged between 25 and 50 ha. All of them registered a plant density of 4000 plants/ha, used drop irrigation systems, and produced blueberries mainly for export as fresh fruit.

2.3. Life cycle assessment

The goal of this analysis was to generate generic life-cycle models of CO, OI, and OA blueberry production systems in order to evaluate the environmental impacts of these practices. The functional unit (FU) was 1 ton of fresh blueberries produced at the farm gate.

2.3.1. System boundary

The system boundaries encompassed all direct inputs and emissions associated with the use of farm machinery (i.e., fuel for field operations and crop irrigation), the production of fertilizers/soil amendments, seed, and pesticides, as well as field-level nitrous oxide (N_2O) and ammonia (NH_3) emissions from fertilizers and crop residues. Inputs and emissions associated with the production and maintenance of farm machinery and infrastructure as well as transportation of inputs were not included, nor were anticipated differences in soil carbon sequestration or methane production. We considered all inputs and processes related to blueberry production that occur within one season year (April to March). We included the emissions related to the production and application of farm inputs and the management and final disposal of outputs. The boundary is set at the harvest moment. Although many producers have their own packing to achieve higher prices for their berries, packing and all management related to the fruit after it leaves the farm was excluded from the analysis. Nursery stage and pruning residue treatments (burning, mulching, recycling in the nursery, or composting) were excluded due to lack of data. We focused on the life cycle of the product from the "cradle to the farm gate".

2.3.2. Data inventory

The life cycle inventory (LCI) stage of a LCA involves collecting relevant data regarding the material and energetic inputs and emissions associated with each stage of the product life cycle. We obtained data for material inputs (fertilizer, fuel, seed, pesticides, etc.) from farmer's interviews, farm administrative records and in situ observations. This study includes the following agricultural factors:

Soil management: includes the emissions caused by producing and applying all fertilizers and soil amendments used.

Pest control: involves all inputs related to pest and disease control and weed management.

Machinery use: involves the use of tractors and farm machinery.

Irrigation: the emissions caused by irrigation are related to the energy consumed by the irrigation system.

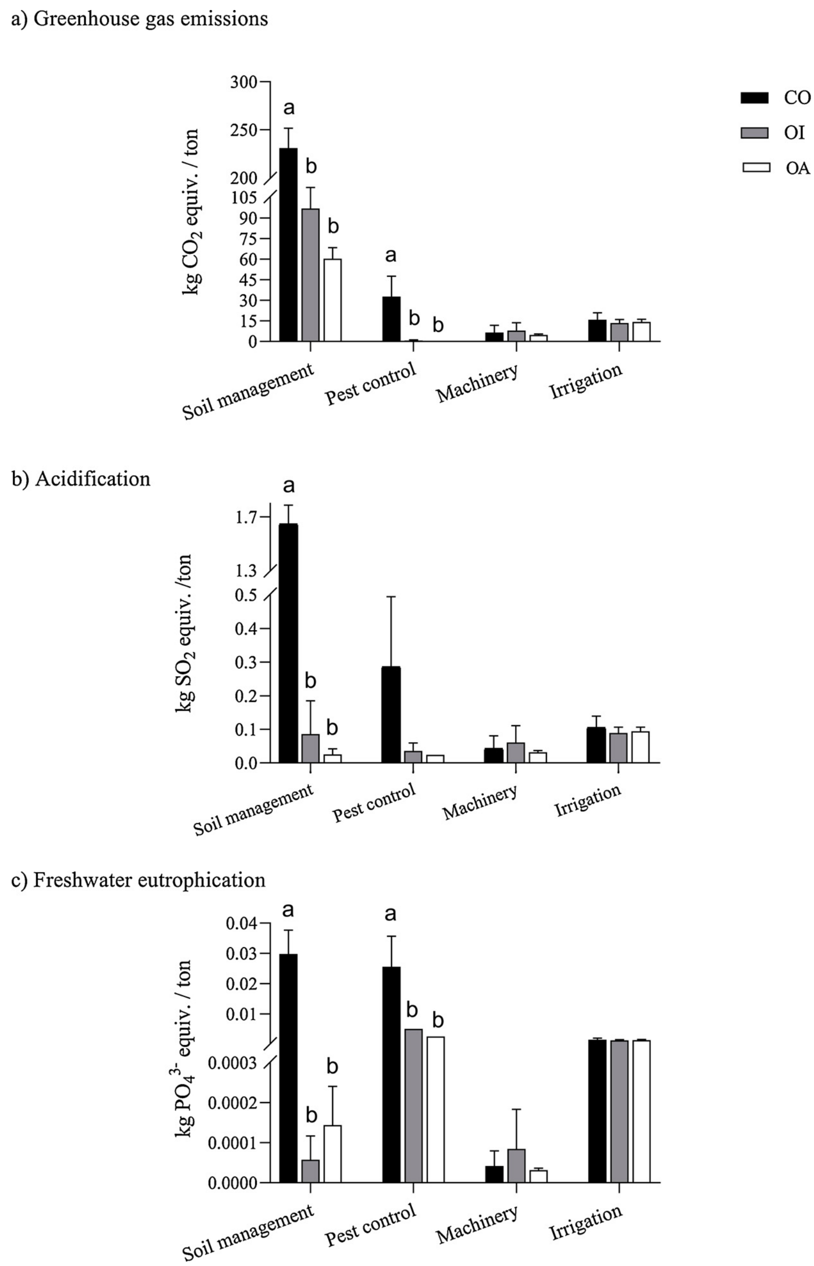

Fig. 3. Contribution of each agricultural factor considered in this study to (a) greenhouse gas emissions, (b) acidification, and (c) freshwater eutrophication for the production on 1 ton of fresh blueberry in conventional orchards (CO), orchards with organic management based on input substitution (OI), and orchards with organic management based on agroecological principles (OA). Bars represent means ± SD. Significant differences (Wilcoxon signed-rank test, BH corrected $p < 0.05$) are denoted by different letters.

2.3.3. Environmental impact assessment

Environmental impact assessment involves calculating the potential environmental burdens associated with specific life-cycle activities by quantitatively expressing all inputs and emissions tabulated in the LCI according to their contributions to a suite of specified environmental impact categories (Pennington et al., 2004). Numerous environmental impact categories have been developed for use in LCA (Pelletier et al., 2015) and should be chosen according to the specific goals of the study at hand. We used the LCA method proposed by the international standard ISO 14040 (2006) and the impact assessment based on the International Panel of Climate Change (Eggleston et al., 2006). We evaluated the following environmental variables:

GHG emissions as a proxy of climate change: GHG emissions were measured as carbon dioxide equivalents (CO_2-equiv.). The major GHG emissions from agriculture are CO_2, methane, and N_2O. The impact of lupine flour, which was the only input not considered in the LCI database, were obtained from Cordes et al. (2016).

Acidification: the major acidifying pollutants from agriculture are ammonia and sulfur dioxide (SO_2). Acidification is quantified in terms of SO_2 equivalents (SO2-equiv.) (Seppälä et al., 2006). Acidifying pollutants impact on soil, ground- and surface waters, biological organisms, and other materials, for example, causing fish mortality, forest decline and the erosion of buildings.

Freshwater eutrophication: eutrophication occurs due to the enrichment of terrestrial and aquatic habitats with plant nutrients, which results in increased growth of plants and algae. This can harm wildlife and ecosystem functioning, and impair the water use for recreation, industry, and drinking (Tuomisto et al., 2012). The main agricultural sources are nitrate, phosphate (PO_4^{3-}), and ammonia. Eutrophication is quantified in terms of PO_4^{3-} equivalents (PO_4^{3-}-equiv.) (Huijbregts and Seppälä, 2001).

2.4. Yields and cost of production of blueberry under different farming practices

We estimated blueberry yield (ton/ha) for each orchard based on commercial production for 2015 season. We registered cost of production and estimated the total variable operational cost of growing blueberries (US $/ha) for 2015 for each farming management. Cost of production was estimated for comparative purposes, and only considered soil and pest management, cultural practices, machinery use, and labor.

2.5. Data analysis

For LCA analysis we used the SimaPro 8.0 LCA software package from PRe´ Consultants (PRe´ 2006). To test for differences in blueberry yield, cost of production, and environmental impact among farm management we used Kruskal-Wallis test (Zar, 2019) since data was non-parametric. When Kruskal–Wallis test was significant, we used Wilcoxon paired comparison test to identify differences between each pair of orchad regime. We performed statistical analyses in R *software* (version 3.5.1, R Development Core Team 2018) using the package "dplyr" (Wickham et al., 2015). We considered p values < 0.05 to be statistically significant in all analyses.

3. Results

3.1. Blueberry yields and cost of production

Although the cost of production differed among agricultural practices (H = 9.85; $p = 0.007$), blueberry yields were similar among management regimes (H = 3.23; $p = 0.199$) (Fig. 1a). OA reported highest yields, of 8.5 ton/ha on average, followed by CO farming, 7.6 ton/ha, and OI with 6.7 ton/ha. OA had the lowest variable production costs, of 2265 US $/ha yr., followed by CO, with 2753 US $/ha yr., and OI, with 3364 US $/ha yr. (Fig. 1b).

3.2. Blueberry life cycle inventory

Table 1 reports the LCI data for the inputs and emissions associated with the cradle-to-farm-gate production of blueberries for CO, OI, and OA. Regarding soil nutrition, nitrogen in CO is mainly added to the soil as urea. In OI and OA, compost is the main soil input. CO are also using eight different pesticides including glyphosate for pest control, and both organic systems use only copper-based pesticides. Additionally, these systems also use biological control agents such as entomopathogenic fungi that are inoculated with the establishment of the crop, and manual control. In relation to machinery and energy use for field operations, all orchards use one or more diesel tractors. OI demand the highest amount of fuel, which is mainly used for spraying and mowing activities. All orchards evaluated use drip irrigation systems which demand a similar amount of electricity (electricity is provided by the national grid).

3.3. Blueberry environmental impact assessment

GHG emissions of CO were higher than emissions of both organic regimes (Fig. 2a; BH corrected p = 0.043) and contribute to global warming, on average, 2.9 times more. Most GHG emissions in CO are originated by these farms' external inputs for soil management and pest control (Fig. 3a). In CO, soil management generates on average 3.8 times more emissions than OA (BH corrected p = 0.043), which is mostly generated by urea and other N-fertilizer (Table 1). The contribution of pest control to GHG emissions is 61 times higher in CO compared to OA (BH corrected p = 0.021) (Fig. 3a).

Regarding acidification, on average CO have an impact 7.7 times higher than OI (BH corrected p = 0.043) and 11.9 times higher than OA (BH corrected p = 0.043) (Fig. 2b). Soil management and pest control had the highest contribution to acidification (Fig. 3b). CO contributions are generated mostly by soil management which is substantially higher than in the organic farms (BH corrected $p < 0.05$), mainly due to fertilizers. On average, pest control in CO generates 9.58 times higher impacts compared to organic orchards, but due to high variability in CO this impact is not significant (BH corrected $p > 0.05$) (Fig. 3b).

Freshwater eutrophication was on average 11 times higher in CO compared to OI (BH corrected p = 0.043), and 14.1 times higher than OA (BH corrected p = 0.043) (Fig. 2c). Soil management impacts were higher in CO than in both organic regimes (BH corrected $p < 0.05$) (Fig. 3c). The main contribution of CO was through the addition of phosphate fertilizers. Similarly, pest control in CO are higher than in organic orchards (BH corrected $p < 0.05$) (Fig. 3c). OA presented slightly lower impact than OI (BH corrected p = 0.043). The main input for pest management in CO was glyphosate, which is a phosphate herbicide, and copper (Table 1). There were no differences among management regimes in their impacts in GHG emissions, acidification or freshwater eutrophication due to machinery and irrigation management.

4. Discussion

Organic farming is often proposed as a solution to reduce agriculture's impacts on the environment (Seufert et al., 2012). However, farmers refuse to adopt an organic production due to lower yields and higher costs in organic compared to conventional agriculture (de Ponti et al., 2012; Seufert et al., 2012; Retamales et al., 2015). In this study, we analyzed three different -and opposite- agricultural systems of blueberry production in a region that is highly representative of blueberry production in Chile. Contrary to the usual expectation, OA achieved the highest yields, and lowest costs of production. Compared to other crop species, blueberries are a robust crop that adapted to acid soils and its agricultural management demands relatively low inputs levels (Montalba et al., 2010). This could partly explain why in our study we found similar yields among management regimes. Yields registered in this study range between 4.5 and 9.5 ton/Ha. These values are comparable to a recent study by Retamales et al. (2015) which reported mean yields of 8.14 ton/ha for 'Legacy' plants of 1–5 years old.

OI and OA registered the lowest impacts for all the categories evaluated: global warming, acidification and freshwater eutrophication, and these impacts were slightly lower in OA compared to OI. Agroecological agriculture is based on using ecological processes that are present in agroecosystems to benefit crop production (Altieri, 2018). This requires a high level of knowledge that is specific to each crop and location (Altieri et al., 2017; Weiner, 2017) in order to maintain the crop system "healthy" with high yields avoiding disequilibrium that lead to problems in nutrition and/or diseases (Montalba et al., 2010). OI are not based on these principles, but rather continue using the "conventional rationality" but with organic certified inputs. This explains the high input and fuel dependence on OI compared to OA, higher production costs, as well as lower environmental impact of OI compared to CO. Additionally, organic inputs are more expensive and less effective for pest control and fertilization compared to conventional inputs, and thus OI production costs are higher and their yields are lower than in CO. Despite these benefits; both conventional -in the first place- and organic farming based on input substitution continue being the main farming systems in blueberry production in southern Chile (Cordes et al., 2016). Agroecological blueberry production requires specific knowledge regarding the crop and local ecological processes, and a paradigm shift of the farmers' mindset (Altieri et al., 2017). Balmford et al. (2018) conducted a meta-analysis and found that modern conventional agricultural systems tend to generate less environmental impacts since they are more land-use efficient (i.e., higher yields per unit of area). Consequently, they would allow for more land sparing and natural areas conservation. On the contrary, in this study, we found that per functional unit (1 ton) of blueberry, highest environmental impacts are achieved by conventional farming systems.

The main contributors to the GHG emissions, acidification, and freshwater eutrophication were soil management. CO and OI rely heavily on external inputs for their management. In particular, soil management in CO rely heavily on highly soluble N-fertilizer which consist in ammonia (urea). This result is in agreement with Girgenti et al. (2013) and Cordes et al. (2016), who found that in blueberries production fertilizers are the main responsible for the carbon footprint at the farm stage. OA also uses external inputs (but locally produced) for soil management but at much lower amounts compared to OI. In OA soil management favors nutrients solubilization by enhancing soil biological activity. This management includes intercropping with species that are incorporated to the crop as green manure, and biological products such as compost tea.

Within each management regime, environmental impacts were variable (Fig. 2). This variation is partly explained by differences in management in terms of type inputs used, and the amount applied (Table 1). In some cases, we found that the four orchards under the same management regime did not used the same input (e.g., only two OI used phosphate rock) and in other cases the four orchards used the same amount of the same input (e.g., copper-based pesticide in OA). Regarding pest control, the high amount of chemicals included in CO explain higher environmental impacts observed. However, compared to OI the impacts are not significantly different. This occurs because one of the CO has extremely low inputs for pest control applying less copper than OI plus a low dosage of glyphosate. Thus, environmental impacts of CO related to pest management have high SD (Fig. 3); if we consider only the three CO that use at least six different inputs for pest control environmental impacts would be even higher compared to organic orchards. Probable explanation for this variability lies in the different mindset of farmers and their consultants. Farmers tend to overuse some inputs based on a risk aversion strategy (*personal observation*) which can have detrimental effects for the crop (e.g., Montalba et al., 2010). In other cases, variability within farming regimes was low or inexistent. For example, OI and OA used only copper-based pesticides and the dose was almost the same in all orchards, which explains the absence of variation in environmental impacts related to pest management within organic regime. Considering this variation allows for a better representation of the blueberry orchards present in our study area, and thus our results are more robust than if we compare theoretical orchards.

5. Conclusions

Globally, environmental impacts generated by agriculture are well documented, but it is also known that the management scheme can make a large difference in these detrimental effects (Altieri et al., 2017). Higher yields can be interpret as a benefit in terms of land sparing for conservation, but higher yields are always not determined by management scheme. Rather, agricultural management should be the focus of the analysis when comparing environmental effects of different management schemes. Clearly, organic management has less detrimental effects for the environment.

Within organic management, in our analysis we found that it is important to distinguish among management schemes. Organic agriculture based on input substitution has higher environmental impacts associated to specific managements, compared to organic based on agroecological principles. When analyzed from an economical perspective, it becomes clear that agroecological management is a better option for farmers, although it can be harder to implement due to lack of knowledge. Policies should provide incentives towards these knowledge and practices, and farmers should make an effort to acquire agroecological knowledge and thus implement more sustainable farming systems.

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