Techno-economic, environmental and social assessment of precision agriculture for stone fruit production

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Abstract

Precision agriculture is a powerful solution to mitigate the environmental impact of agricultural systems, optimize crop inputs and cost reduction. The aim of this work is to analyze the benefits of precision farming practices (irrigation, fertilization and phytosanitary treatment) through a life cycle sustainability assessment (environmental, economic and social impacts) using a detailed life cycle inventory for stone fruit production compared to traditional production. The 8-year life cycle inventory was provided by a local producer in southern Spain. The system boundaries include a "gate to farm gate" approach using 1 kg of stone fruit as the functional unit. The streamlined analysis incorporates environmental, life cycle cost and social risk analysis for this crop production. The results show that the reduced input requirements of the precision agriculture scenario led to lower environmental damage, reduced economic costs and lower social risks, with average impact reductions ranging between 20-30% in most sustainability categories.

Keywords: life cycle sustainability assessment; variable application of inputs; nectarine.

1. Introduction.

Spain was the second largest exporter of fruit and vegetables in the world and the main supplier of fruit to the EU in 2020, with an annual production of €14,595 M (MAPA 2021). In 2021, stone fruit exports reached a record value of €1370 M, with an export volume of 9,476,665 t. The Region of Murcia is responsible for 27% of Spain’s stone fruit production. However, the sector is facing a crisis, mainly due to the sharp increase in production and processing costs (e.g. fertilizers, phytosanitary products, plastics, electricity and fuel), the geopolitical situation and the effects of climate change (e.g. late frosts, droughts, heatwaves...). In addition, consumers are changing their purchasing preferences and are increasingly concerned about the conditions under which food is produced and whether their purchase has undesirable environmental and social impacts.

In order to understand the holistic impact of products on the market, a methodology called Life Cycle Sustainability Assessment (LCSA) has been developed over the last 20 years, which assesses and integrates the areas of environmental, economic, and social impacts (Klöpffer 2003). Table 1 provides a summary of studies using the LCSA method on different agricultural products. The authors use the same theoretical framework of LCSA (Environmental Life Cycle Assessment (LCA) + Life Cycle Costing (LCC) + Social Life Cycle Assessment (s-LCA)), but the studies differ in the methods, impact indicators and databases used.

Precision agriculture (PA) techniques are currently a powerful solution for reducing the environmental impact of agricultural systems (Bacenetti et al. 2020). They contribute to a precise and optimized use of crop inputs (fertilizers, phytosanitary products and water) through variable application (Zude-Sasse et al. 2016), which also leads to reduced costs (Heege 2013). The aim of this study is to assess the sustainability in all three impact areas (environmental, economic and social) of the application of PA in the stone fruit life cycle.

2. Materials and method.

This study describes the impacts of the production of stone fruit (Prunus persica var. nucipersica) assessed by LCSA (LCA+LCC+s-LCA) according to the UNEP / SETAC theoretical framework (UNEP 2011). Inventory data were used from an orchard located in the municipality of Cieza (Murcia) in south-eastern Spain.
The study area covers 40 ha with 667 plants per ha and produces an average of 35 t ha⁻¹ of fresh fruit, considering production data over a period of 8 years. The study was carried out considering the principles of ISO 14040 – 14044 (ISO 14040 2006; ISO 14044 2006), which includes four iterative stages: Goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation. The former two stages are described in sections 2.1 and 2.2, and the latter two in section 3. Results and discussion /interpretation. Sections 2.5, 2.6 and 2.7 explain how the environmental, economic, and social aspects have been assessed.

2.1. Goal & Scope definition. The objective of this study is to evaluate the environmental, economic and social life cycle performance of a stone fruit production system, considering two scenarios: variable input application using PA technologies and uniform input application using traditional (T) technologies. The functional unit (FU) was defined as 1 kg of nectarines, unpackaged (in bulk), at the farm gate. The system boundaries consider only the gate – to – gate (core) procedures of the total value chain for the assessment of the three impact areas, as shown in Figure 1. Both scenarios follow the same system boundaries and FU, but differ in the dose estimation methods and technologies used to apply the inputs. In this work, PA techniques focus on sensing-recording (sensors mounted on ground stations that collect information to characterize spatial and temporal variability of key agricultural parameters such as yield, soil fertility, moisture content and plant physiological state) and response technologies (hardware and software that together can vary the application of agricultural inputs in space and time in the field).

The irrigation schedule in the PA scenario is based on the calculation of adjusted crop evapotranspiration (ETc adj) and the use of volumetric soil moisture probes and flowmeters with networked data loggers, together with a private on-site weather station. The traditional scenario follows an irrigation schedule based on the calculation of crop evapotranspiration (ETc) and weather data from the SIAM station network (SIAM 2020).

Figure 1. Life cycle and system boundaries using the gate-to-gate approach (yellow square).

The fertilizer plan in the PA scenario considers yields per plot sector, two soil and leaf analyses and chemical analyses of fertigation and drainage water carried out throughout the season. In the traditional scenario, the programme describes average production yields of the plot, one soil analysis per season and fertilizer supplier's recommendations.

The phytosanitary programme in the PA scenario is based on disease warnings from the company (based on weather data and specific risk models) and monitoring by counting the presence of insects, mainly controlled by pheromone traps. In the traditional scenario, the supplier’s fungicide and insecticide application programme is only considered according to calendar and crop stage.
2.2. Life cycle inventory analysis. Table 2 shows the inventory of inputs per season in the nectarine life cycle by FU. The inventory was compiled using data from a fruit production (both scenarios) and processing company in Murcia. Background secondary inventory data for energy use, transport, machinery and irrigation were sourced from Ecoinvent v3.7.

Table 2. Life cycle inventory by FU in precision agriculture (PA) vs. traditional (T) scenarios. * Active ingredient

<table>
<thead>
<tr>
<th>Crop Production</th>
<th>Process inventory</th>
<th>Economic inventory</th>
<th>Process inventory</th>
<th>Economic inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CROP INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fertilization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-0-0-46 kg</td>
<td>1.22</td>
<td>1.57E-02</td>
<td>1.92E-02</td>
<td>1.33E-02</td>
</tr>
<tr>
<td>0-0-0-28 Ca</td>
<td>1.17</td>
<td>8.02E-03</td>
<td>9.95E-03</td>
<td>7.16E-03</td>
</tr>
<tr>
<td>21-0-0-60 SO3</td>
<td>1.21</td>
<td>7.32E-03</td>
<td>8.86E-03</td>
<td>6.22E-03</td>
</tr>
<tr>
<td>0-3-0-0</td>
<td>1.2</td>
<td>5.15E-03</td>
<td>6.14E-03</td>
<td>4.56E-03</td>
</tr>
<tr>
<td><strong>Irrigation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water m³</td>
<td>3.30E-01</td>
<td>1.24E-01</td>
<td>4.26E-02</td>
<td>9.03E-02</td>
</tr>
<tr>
<td>Electricity kWh</td>
<td>3.70E-01</td>
<td>4.24E-02</td>
<td>1.57E-02</td>
<td>2.97E-02</td>
</tr>
<tr>
<td><strong>Phytosanitation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pesticides kg</td>
<td>5.30E-01</td>
<td>2.67E-05</td>
<td>1.42E-03</td>
<td>2.40E-05</td>
</tr>
<tr>
<td>Insecticides kg</td>
<td>5.20E-01</td>
<td>1.87E-04</td>
<td>9.71E-03</td>
<td>1.68E-04</td>
</tr>
<tr>
<td><strong>PA technologies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical staff hr</td>
<td>1</td>
<td>3.60E-03</td>
<td>6.05E-03</td>
<td>7.46E-02</td>
</tr>
<tr>
<td>Machinery hr</td>
<td>1.60E-02</td>
<td>8.05E-03</td>
<td>1.34E-02</td>
<td>7.76E-03</td>
</tr>
<tr>
<td>Fuel l</td>
<td>1.00E-03</td>
<td>1.46E-03</td>
<td>2.30E-03</td>
<td>1.11E-03</td>
</tr>
<tr>
<td>Transport km</td>
<td>1.10E+00</td>
<td>2.38E-03</td>
<td>3.11E-02</td>
<td>2.41E-02</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>1.97E+01</td>
<td>7.16E-03</td>
<td>2.90E+01</td>
<td>3.80E+01</td>
</tr>
</tbody>
</table>

2.3. Environmental impact assessment. The analysis was performed on Simaprog v9.2, using as a reference the product category rules (PCR) for fruits and nuts (EPD 2019) and the EF 3.0 assessment method (ELCD 2020). The impact categories considered were climate change, photochemical ozone formation (POF), acidification (A), eutrophication of freshwater (E) and water use (W).

2.4. Economic assessment. In both production scenarios only gate-to-gate costs were considered (i.e. from the gate of purchase of inputs and resources to the farm gate). The economic feasibility assessment includes only the purchase costs (C) for the company as defined in equation (1). The market prices of phytosanitary and fertilizers were obtained from the company Frutas Esther S.A. 2022. The price of water correspond to the local irrigation association of Cartagena (Murcia, Spain) (CRCC 2022). The electricity tariff correspond from the value of the national mix (Som Energia 2022). The price of fuel was obtained from the Spanish confederation of freight transport (CETM 2022). The price of PA management was obtained from various specialized companies: Soil and leaf analysis (CSR Laboratorio 2023); fertiliser and irrigation online management system (ModpoW 2023); traps, attractants and pheromones (PROBODELT 2023); disease warning software and weather station (TAMIC. 2022). Table 2 shows the economic costs for the PA and traditional scenerios, a comparative analysis is provided in results section 3.2.

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Unit</th>
<th>Traditional</th>
<th>Precision agriculture</th>
<th>Diff. %</th>
<th>PAtech %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>kg CO2 eq</td>
<td>9.33E-02</td>
<td>7.01E-02</td>
<td>-24.8</td>
<td>0.36</td>
</tr>
<tr>
<td>Photochemical ozone formation</td>
<td>kg NMVOC eq</td>
<td>5.87E-04</td>
<td>4.68E-04</td>
<td>-20.3</td>
<td>0.18</td>
</tr>
<tr>
<td>Acidification</td>
<td>mol H+ eq</td>
<td>7.71E-04</td>
<td>5.83E-04</td>
<td>-24.3</td>
<td>0.25</td>
</tr>
<tr>
<td>Eutrophication, freshwater</td>
<td>kg P eq</td>
<td>1.51E-05</td>
<td>1.24E-05</td>
<td>-17.6</td>
<td>0.25</td>
</tr>
<tr>
<td>Water use</td>
<td>m³ depriv.</td>
<td>1.29E-01</td>
<td>9.04E-02</td>
<td>-29.9</td>
<td>0.05</td>
</tr>
</tbody>
</table>

2.5. Social risk assessment. The was carried out using the sectorized economic inventory for the conventional and PA scenarios and the social risk data from the Social Hotspot Database (SHDB) (UNEP 2020). Costs were converted (deflator) from 2022 € to 2011 USD according to official inflation and currency conversion ratios.

3. Results and discussion.

3.1. Environmental impact. Table 3 describes the emissions of 9.33E-02 kg CO2 per FU in the traditional scenario and 7.01E-02 kg CO2 per FU in the PA scenario. The largest decrease between the scenarios was in water use with 29.9%. The smallest decrease between the scenarios was in eutrophication with 17.6%. The PA scenario shows an average decrease of the indicators of 23.4%. On average, 0.22% of the difference in environmental impact between the scenarios is due to the introduction of precision agriculture technology. According to Núñez-Cárdenas et al. 2022, the implementation of PA technologies in fertilization, irrigation and phytosanitary reduced the average environmental indicators in stone fruit crops by 21%.

Table 3. Environmental impacts assessment by FU. (Diff. %: reduction comparing Traditional vs. PA scenarios. PAtech %: impact of the PA technologies in PA scenarios).

3.2. Economic results. Figure 2 illustrates the average economic savings in crop input consumption, ranging from 10% for phytosanitary, 15% for fertilizers and 30% for water and electricity use. Savings in fuel, transport and machinery were -23%, -15% and -10% respectively. The average cost difference between the scenarios was 8%. The costs of cultural management (thinning, pruning, harvesting, etc.) are not included as they are not affected by PA technologies.

Figure 2. Economic viability results per functional unit between Traditional and Precision agriculture scenarios.

The cost of technical staff is higher in the PA scenario because more hours of monitoring are required. The net saving of the PA technologies scenario was 532 € ha⁻¹yr⁻¹ (gross saving 1064 € ha⁻¹yr⁻¹). The investment cost of PA technologies and technical staff was 532 € ha⁻¹yr⁻¹.
Bellvert et al. 2020, analyzed the economic savings of PA technologies in electricity and irrigation water use corresponding to a 59% increase in gross profit.

Specific life cycle social analysis would need to be carried out to corroborate these findings. Overall, reduction in environmental, economic and social impacts caused by the implementation of PA were estimated to range between 20-30%.

Acknowledgments
This study was funded by FEDER/Ministerio de Ciencia e Innovación (Agencia Estatal de Investigación, Spain) under project RTI2018-099139-B-C22 (KARPO LIFE) and by the National Agency for Research and Development (ANID)/ Scholarship Program/doctatorado becas Chile/2019 – 72200450 and Universidad de Magallanes (Chile).

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