Science of the Total Environment 845 (2022) 157342

Contents lists available at ScienceDirect

Science of the Total Environment

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

Determining the environmental and economic implications of lupin cultivation in wheat-based organic rotation systems in Galicia, Spain

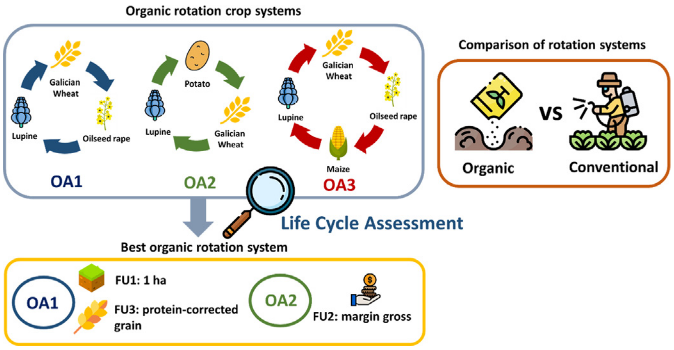
Ricardo Rebolledo-Leiva [a,*], Fernando Almeida-García [b,c], Santiago Pereira-Lorenzo [c], Benigno Ruíz-Nogueira [c], María Teresa Moreira [a], Sara González-García [a]

[a] CRETUS, Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain
[b] Grupo Da Cunha, 15175 Carral, Spain
[c] Department of Crop Production and Engineering Projects, High Polytechnic School of Engineering, University of Santiago de Compostela, Spain

HIGHLIGHTS

- Environmental and economic performance of lupin in three wheat-based rotations
- Three functional units were used: land management, gross margin and protein-content.
- Lupin-wheat-rapeseed is the best rotation based on land and economic functions.
- Organic rotations only have a gross margin 6 % to 15 % lower than conventional ones.
- Except for acidification, organic systems are less impactful than conventional ones.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Legumes
Life cycle assessment
Crop rotation
Cropping systems
Nitrogen fertilisation
Functional unit

ABSTRACT

Crop rotation represents a potentially sustainable strategy to address environmental problems of intensive agricultural practices, such as soil degradation, biodiversity reduction, and greenhouse gas emissions. This manuscript assesses the environmental and economic implications of introducing lupin cultivation into winter wheat-based rotation systems under an organic regime in Galicia, Spain. Life Cycle Assessment methodology was used to determine the environmental impacts of three rotation systems over a six-year period: lupin → wheat → rapeseed (OA1), lupin → potato → wheat (OA2), and lupin → wheat → rapeseed ‖ maize (OA3). For a robust assessment, three functional units were applied: land management (ha), economic indicator (gross margin in euros) and protein content (1 kg of protein-corrected grain). Moreover, the environmental profiles were compared with rotation systems without lupin crop in a conventional regime. In terms of Global Warming, impacts of about 2214, 3119 and 766 kg $CO_2eq \cdot ha^{-1}$ were obtained for OA1, OA2 and OA3, respectively. Moreover, OA1 is the best rotation in terms of land and protein. Meanwhile, OA2 rotation is the best choice in the economic function, as it obtained the highest level of gross margin (5708 $€ \cdot ha^{-1}$). Furthermore, with the exception of acidification, organic systems are less impactful than conventional systems. Ammonia emissions from the use of manure are the reason for these higher impacts. Organic rotations OA1 and OA2 have about 6 % or 15 % less gross margin than their conventional counterparts, respectively, however, an increase of 28 % was obtained for rotation OA3. This study helps decision-makers to implement environmentally and economically viable strategies.

---

* Corresponding author.
E-mail address: ricardo.rebolledo.leiva@usc.es (R. Rebolledo-Leiva).

http://dx.doi.org/10.1016/j.scitotenv.2022.157342
Received 29 March 2022; Received in revised form 17 June 2022; Accepted 9 July 2022

1. Introduction

Society is facing a scenario of steady population growth, changing dietary patterns and resource constraints as main challenges influencing the food security scenario, which motivates the intensification of agricultural production (Popp et al., 2010; Prechsl et al., 2017). Agricultural activities are a major contributor to climate change, accounting for 52 % and 84 % of global methane (CH_4) and nitrous oxide (N_2O) emissions, respectively, as well as the eutrophication problems associated with the leaching of excess nitrogen and phosphorus nutrients in the agricultural area (Cai et al., 2018; Prechsl et al., 2017).

Over the decade 2021–2030, the cereal production is expected to rise by 336 Mt. (OECD, 2021). The importance of cereals lies in the high levels of carbohydrates, dietary fibre, and protein. Wheat is the most widely cultivated cereal in the world (Le Gouis et al., 2020) and represents a key crop for food security (Erice et al., 2019). Spain produced around 25.4 Mt. of cereals in 2020, with wheat and barley as the main crops (Ministerio de Agricultura, 2021). In Galicia (north-western Spain), native wheat grain can be classified into the "Caveeiro" and "Callobre" varieties with more starch and less gluten in relation to durum wheat. This cereal is used to produce a high-quality national reference bread, recognised for its taste, texture and aroma, due to the use of sourdough and longer fermentation and baking times in stone ovens (Câmara-Salim et al., 2020). According to the Protected Geographical Indication (European Union, 2019), the cultivation of Galician autochthonous wheat is expected to double in the coming years.

The intensification of crop production and its high input consumption leads to diverse environmental problems, depletion of non-renewable energy resources, biodiversity reduction, water pollution, and greenhouse gas emissions (GHG) (González-García et al., 2021; Stoate et al., 2001). A relevant input in the cropping system is related to fertilisers that provide the required nutrients, especially nitrogen, for crop growth. However, only a fraction of the nitrogen provided is consumed by the crop plant, the major fraction (above 50 %) is taken up by the soil, as well as can be lost directly as N_2O by leaching (nitrate, NO_3^-) or volatilization (ammonia, NH_3 and nitrogen oxides, NOx) (Liu et al., 2016; Wowra et al., 2021), triggering environmental issues such as eutrophication and global warming.

An interesting sustainable agricultural cropping strategy can be based on crop rotation systems, which correspond to a sequence of different agricultural crops grown on the same field. Growing different crops in chronological sequence has positive synergies, with benefits for the subsequent crop provided by the previous one (Brankatschk and Finkbeiner, 2015). Some of these benefits are related to improved phytosanitary conditions, improved nitrogen management and consequently reduced related environmental impacts (MacWilliam et al., 2014; Nemecek et al., 2015). Incorporating legumes in crop rotations brings benefits by preventing pests and fixing atmospheric nitrogen, which reduces fertiliser requirements (Köpke and Nemecek, 2010). Furthermore, this practice can improve yield, grain quality and protein content in the following cereal crop (MacWilliam et al., 2014). In this study, the attention will be focus on lupin, a grain legume habitually ingested as appetizer or in form of flour. Lupin is rich in unsaturated fats and proteins (40 % content, higher than lentil and chickpea) and is considered one of the legumes with the highest agronomic growth in Europe, which could help reduce protein dependence on third countries (van de Noort, 2016). In particular, the relevance of evaluating the introduction of lupin into Galician winter wheat rotation systems is to evaluate new forage production strategies to avoid dependence on imported soybeans by local farmers. In addition, organic production of Galician autochthonous wheat faces problems related to weed control due to the impossibility of using herbicides, which can be tackled by introducing a legume into intensive wheat production for the production of autochthonous Galician bread. This, when the approval of the Protected Geographical Indication Pan Gallego by the European Union (European Union, 2019) seems to open new opportunities to produce wheat of the native "Callobre" and "Caaveiro" varieties. Moreover, the implementation of rotation systems can also be beneficial for bakeries, as in addition to improving protein content, flour yield and grain specific weight are improved.

The design of a sustainable rotation system must consider the various environmental impacts generated, not only those associated with the crop, but also those derived from the resources consumed. Life Cycle Assessment (LCA) is a method that quantifies the multiple environmental impacts throughout the life cycle of the system under evaluation. This tool has been successfully applied in several studies on agricultural systems (Câmara-Salim et al., 2021; Iriarte et al., 2021; Vásquez-Ibarra et al., 2021a, 2021b). Through this method, it is possible to determine the stage of the life cycle that represents the greatest contribution to environmental impacts, and to propose improvement plans to reduce them. Despite the potential environmental benefits of rotation systems, evidence of the prospective economic benefits is also required to encourage farmers to implement these systems, introducing legumes as co-products in cereal-based rotation systems.

The aim of this study is to assess the environmental impacts and economic implications of the introduction of lupin as an alternative crop in Galician wheat-based rotation systems, within the framework of organic farming. For this purpose, three rotation systems were evaluated to identify the most favourable rotation system from an environmental and economic point of view. Furthermore, this study seeks to identify possible synergies among the crops within the rotation system, considering the effects that returning the straw into the soil has on the following crop. In addition, the rotation systems studied were compared with rotation systems without lupin cultivation, under a conventional regime. It is therefore important to determine whether the introduction of lupin cultivation can lead to a production yield closer to the conventional regime, and what are the environmental and economic consequences between these two land management systems. Through this study, it is hoped to provide recommendations for sustainable practices to motivate farmers and stakeholders to mitigate environmental burdens by improving the economic performance of their agricultural systems.

2. Materials and methods

2.1. Description of the crop rotation systems under organic regimen

In this study, the agricultural systems evaluated are dedicated to the Galician autochthonous winter wheat (Ge-WW) production under organic farming. Moreover, the crop rotation systems consider potato (PT), maize (MZ), oilseed rape (OSR), and lupine (LPN) as co-products. Therefore, the three rotations evaluated are: *i*) OA1: Ge-WW → OSR → LPN; *ii*) OA2: LPN → PT → Ge-WW; *iii*) OA3: LPN → Ge-WW → OSR-G ‖ MZ. All scenarios were grown on a six-year rotation cycle. In addition to the main crop (Ge-WW), the co-products are sold. In the OA3 rotation system, OSR-G is an intercrop that is not harvested. It is sown in late summer to achieve a good implantation and cover for the next crop, serving as nutrient for maize cultivation.

2.1.1. Galician winter wheat and lupine cultivation

The organic cultivation of Ge-WW follows a strict limitation in the used of mineral fertilisers and synthetic pesticides. The cultivation starts with a chisel ploughing activity, followed by organic fertilisation with poultry manure. This is followed by sowing (150 kg seeds·ha^{-1}) combined with tillage, which is performed in November. As no pesticides are employed, a mechanical treatment is applied to eliminate weeds. Foliar fertilisation (*Nitromyel* 30-0-0, 3 L·ha^{-1}) is then supplied to the leaves of the plants, which is acceptable in organic regimen (González-García et al., 2021). Finally, the wheat grain is harvested in July, leaving all the straw in the field.

As far as LPN is concerned, the crop requires few operational activities. The process starts in February with mouldboard ploughing, followed by mineral fertilisation with *Physalg*® (0–8-15), which is authorised in organic regimen (CAAE, 2020). This is followed by combined sowing (150 kg seeds·ha^{-1}) and tillage performed in October. Finally, the lupin is harvested in August with a yield of 2.7 t·ha^{-1}, leaving the straw completely in the field. A summary of the agricultural activities involved is detailed presented in Table A1 in the Supplementary Materials.

2.1.2. Oilseed rape, potato, and maize cultivation

For OSR cultivation, the process starts with two organic fertilisations with poultry (5 t·ha^{-1}) and cow manure (12 m^3·ha^{-1}) with chisel ploughing in between. After fertilisation, seeding combined with soil tillage is performed in September, followed by mechanical weeding. The OSR crop receives as nutrient input all the straw obtained from the previous Ge-WW crop in OA1 and OA3. The OSR is harvested in June with a yield of 2.5 t·ha^{-1} in OA1, and the straw is left in the field. In the OA3 system, OSR-G corresponds to an intercrop that will not be harvested, since the biomass serves as a nutrient for the following crop, i.e., the MZ crop. Thus, in the OSR-G crop, no fertilisation or mechanical treatment takes place. The sowing process is performed with a combined rotary tiller with seed driller, while the biomass is harvested using a brush cutter (i.e. shredder) with a working width of about 2.5 m. A summary of the agricultural activities for OSR-G in OA3 system is detailed presented in Table A2 in the Supplementary Materials.

The MZ cultivation starts with two applications of organic manure (poultry: 8 t·ha^{-1} and cattle: 15 m^3·ha^{-1}) with a mouldboard and chisel ploughing in between. After fertilisation, tillage and sowing (30 kg·ha^{-1}) activities are performed in May. This is followed by mechanical and insecticide treatment (*Spinosad* 48 %) before harvesting. The organic crop MZ receives as nutrient input the total biomass left in the field by the previous crop OSR-G in the OA3 system. The maize silage is harvested in October with a yield of 25 t·ha^{-1} and the straw is left in the field (2.5 t·ha^{-1}).

As for the PT crop, the process starts with mouldboard and chisel ploughing, followed by organic and mineral fertilisation. The former with poultry manure from organic farms (5 t·ha^{-1}), and the latter with *PatentKali* (30 % K, 250 kg·ha^{-1}), allowed in the organic farming regime. Then, a tillage activity is realized, followed by the sowing process performed in April. In addition, a reduced dose of insecticides and fungicides is applied along with the mechanical treatment. The potato crop receives all the straw from the previous lupin crop in OA2 as nutrient input. The potato is harvested in September with a yield of 20 t·ha^{-1} and the residual biomass (10 %) is used for animal feed.

The agricultural activities involved in the cultivation of Ge-WW, OSR, PT and MZ are obtained from González-García et al. (2021).

2.2. Description of crops production under conventional regimen

In the case of Galician winter wheat crop, field preparation requires mouldboard ploughing and milling, followed by sowing (150 kg of seeds·ha^{-1}). Several agrochemicals are then applied: herbicides (*chlortoluron* and *diflufenican*), mineral fertiliser (CAN 27 %) and fungicide (*tebuconazole*). Oilseed rape production starts with chisel ploughing and mineral fertilisation with NPK (8-15-15, 350 kg·ha^{-1}), followed by a combined soil tillage and sowing (4 kg seeds·ha^{-1}). In addition, post emergence fertilisation (CAN 27 %) and herbicide treatment are applied. Regarding potatoes, the cultivation starts with a mouldboard and chisel ploughing. This is followed by mineral fertilisation with CAN 27 %, followed by the sowing process. Herbicide treatment is carried out with metribuzin 70 % and bentazon 48 %. Finally, in maize cultivation, mouldboard and chisel ploughing is carried out first, followed by mineral fertilisation (NPK 8–15-15) and tillage. Sowing is combined with the application of an insecticide (*Lambda Cyhalothrin* 0.4 %). During the growth of the crop, a second fertilisation (CAN 27 %) and weed treatment are applied. For more details on conventional cultivation, please see González-García et al. (2021).

2.3. Life cycle inventory and assumptions

2.3.1. System boundaries

The cropping system boundaries follow a *cradle-to-farm gate* approach (see Fig. 1). Thus, the environmental assessment of each crop included the extraction (e.g., fossil fuels and minerals), raw materials and equipment (e.g., seeds, fertilisers, herbicides, insecticides, fungicides, and agricultural machinery) as well as use (tailpipe and tyre abrasion emissions), maintenance and final disposal of agricultural machinery. Furthermore, the scope considered for each crop within the rotation corresponds to those activities after the harvest of the previous crop until its harvest.

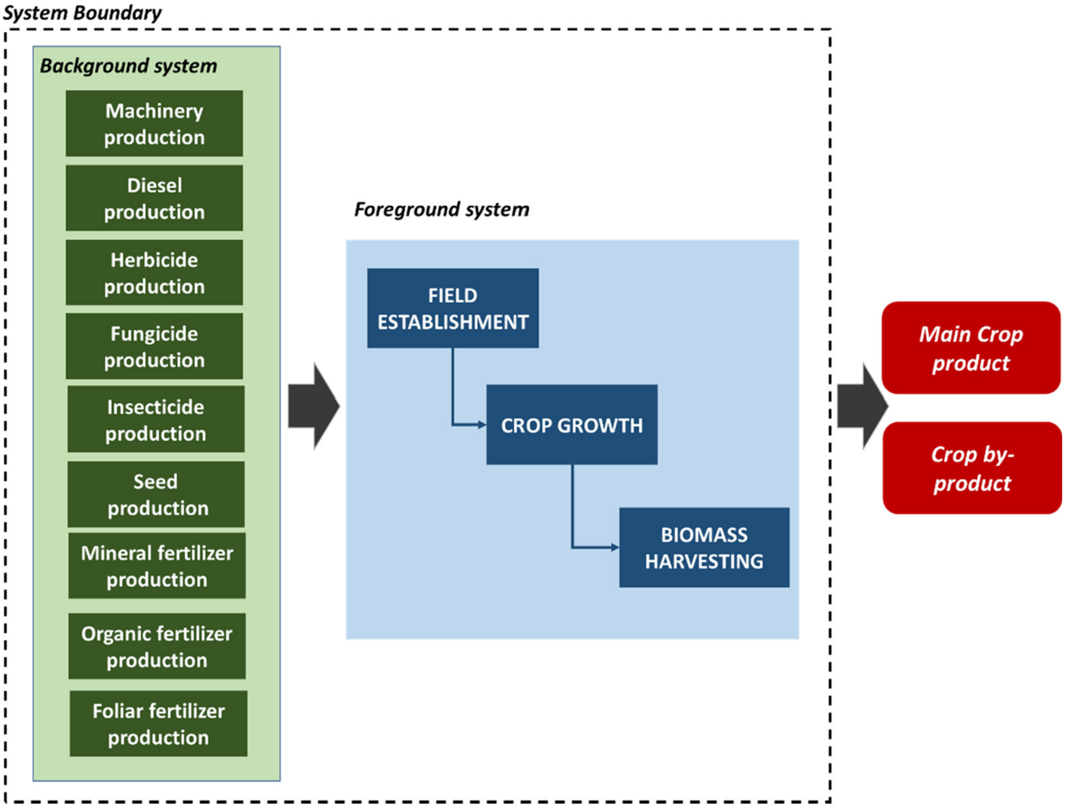


Fig. 1. The system boundary of each crop in the rotation system.

The inventory of the cropping system includes primary and secondary data. The first one collected through the farmer surveys is related to the foreground system and corresponds to operating hours ($h \cdot ha^{-1}$), diesel consumption ($L \cdot h^{-1}$), fertilisers and agrochemicals application ($kg \cdot ha^{-1}$) and yields of products and by-products ($t \cdot ha^{-1}$). The second one associated with background systems is obtained from the Ecoinvent® database 3.6v (Wernet et al., 2016), corresponding to the production of resources consumed (fertilisers, agrochemicals, seed, diesel and machinery). The machinery used in each crop cultivation ($kg\ machinery \cdot h^{-1}$) was estimated by considering the lifetime of the agricultural machinery available in the Ecoinvent® database 3.6v and combined with the information on operating hours and weights collected through the surveys. In addition, tailpipe and tyre emissions were obtained from the Ecoinvent® 3.6v database, based on diesel consumption and machinery usage time for each system.

2.3.2. Functional units and allocation method

Agriculture is a multifunctional system that mainly focuses on commodity production (productive function), preservation of sustainable land use (land management function) and income generation (financial function) (Goglio et al., 2014; Nemecek et al., 2011). Therefore, defining a functional unit (FU) that adequately represents the main objective of these systems is a challenging task. Accordingly, three different FU will be used in this study. The first one refers to the functional unit of land management (FU1: ha) to determine the best management option that minimises environmental impacts based on land availability. The second refers to the economic function (FU2: gross margin, €) to determine the management alternative that produces the highest gross margin with the lowest environmental impact, i.e., an eco-efficiency approach. The third refers to the main target of the cropping system, which is to provide a high-quality wheat grain to produce Galician bread. Thus, the protein content (FU3) is selected as the unit of comparison. As mentioned by MacWilliam et al. (2014), the introduction of pulses increases the yield and protein content of the following cereal crop. This leads to a better rheological behaviour of the dough (water absorption capacity, development time, weakening and stability) in bread production. Therefore, this FU aims to reflect the production of a high-quality wheat grain (consequently a high-quality bread). Thus, the FU3 is defined as 1 kg of 15.1 % of protein-corrected wheat grain (MacWilliam et al., 2014).

The rotation system is considered as a complete cropping system, following the recommendation of Goglio et al. (2018). In this sense, the residual biomass of the crop is returned to the field, so no co-products are obtained. Consequently, no allocation method is necessary (Câmara-Salim et al., 2021).

2.3.3. Direct and indirect emissions from the field

Direct and indirect emissions from the field generated by fertiliser and agrochemical applications were also considered for the environmental assessment where applicable. Thus, N_2O emissions were estimated according to the Intergovernmental Panel on Climate Change (IPCC, 2019). Nitrogen dioxide (NO_2) and NH_3 emissions were determined according to the European Monitoring and Evaluation Program and the European Environmental Agency (EMEP/EEA, 2019). In addition, phosphorus (PO_4^{3-}) leaching and runoff (Prasuhn, 2006) and NO_3^- leaching (Faist Emmenegger et al., 2009) were considered. N_2O emissions to air are related to impact categories such as Global Warming Potential and Stratospheric Ozone Depletion. NO_2 and NH_3 emissions to air are responsible for Acidification, meanwhile, phosphorus and NO_3^- emissions to water are related to Freshwater and Marine Eutrophication, respectively. Finally, pesticides emissions were estimated based on the Product Environmental Footprint Category Rule (European Commission, 2018).

Poultry and cow manure was applied in agricultural activities. According to information provided by farmers, 50 % of the manure is used for energy purposes on the farms, while the rest is used as biofertiliser, which can generate an economic revenue. An economic allocation approach was considered to distribute the environmental burdens of agricultural activities among the co-products obtained (manure, electricity, and animal products). In this sense, an allocation factor of 1 % was established for poultry manure based on the poultry farm inventory data (González-García et al., 2014). As for the cow manure (Cortés et al., 2021), an allocation factor of 4.1 % was considered.

2.3.4. Direct and indirect land use change

Land use change (LUC) is a major source of impacts on the life-cycle environmental performance of agricultural systems (González-García et al., 2021; Schmidt et al., 2015). The impacts associated with LUC caused by land use consider two approaches: direct land use change (dLUC) and indirect land use change (iLUC). The dLUC represents changes in biomass and soil carbon content that occur on the land linked to land use, while iLUC refers to carbon changes that are not directly related to land use (Schmidt et al., 2015). In this study, both LUCs were considered to assess changes in soil carbon content due to the return of residual biomass to the field. Following the seven-step biophysical model (Schmidt et al., 2015), the emission factor iLUC for agricultural land used per cropping system over a six-year period was 289 kg $CO_2eq \cdot ha^{-1}$. Regarding dLUC, harvesting in Ge-WW focuses only on grain and straw is left in the field. The same applies for oilseed rape and potatoes, where only the seeds and tubers were harvested, leaving the straw and leaves in the field.

Likewise, whole maize and lupin plants were removed, leaving the residual biomass in the field. Consequently, changes in soil organic composition occur. In this regard, it was assumed that approximately 16 % of them will be stored in the soil in the long term (Fang et al., 2019) with a carbon content of 49 % for wheat (Brandão, 2012; IPCC, 2019), 47 % for lupin (Tizazu and Emire, 2010), 42 % for maize (Pei et al., 2015), and 41 % for rapeseed (Peterson and Hustrulid, 1998; Rebolledo-Leiva et al., 2022). Thus, the increase in soil carbon content is considered an environmental credit. In addition, the remaining 84 % of the carbon content of the residual biomass has to be emitted; however, this emission was not taken into account in the assessment, as both fluxes were assumed to occur in the same year. The decomposition of the residual biomass during the following years was considered for the same reason.

2.4. Environmental impact categories

In order to determine the potential environmental impacts based on the life cycle inventory of the rotation systems, the ReCiPe 2016 V1.04 Hierarchist midpoint world method (Huijbregts et al., 2017) was chosen. This method provides characterization factors representative of the global scale, and it is one of the most employed (Borghesi et al., 2022), since it is an improvement on ReCiPe 2008, and its predecessors CML 2000 and Eco-indicator 99. Thus, the ReCiPe method is updated frequently. The hierarchist perspective has been considered since it is considered the most balanced of the three proposed by the method (Vitale et al., 2018). The environmental impact categories frequently used in the environmental assessment of agricultural systems were considered: global warming (GW), stratospheric ozone depletion (SOD); terrestrial acidification (TA), freshwater (FE) eutrophication, marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), and fossil resource scarcity (FRS). The SimaPro software 9.3.0.2 (PRé Consultants, 2020) was employed to model the rotation systems.

2.5. Comparing rotation systems under organic and conventional regimen

In order to evaluate the advantages and disadvantages of the introduction of lupin cultivation in rotation systems under organic farming (OA), the results are compared with rotation systems without lupin cultivation under a conventional regime (CR). In this way, the comparison will reflect two opposing management practices that are mainly applied in Galician wheat grain production.

The environmental profile of Galician winter wheat rotations under a conventional management are obtained from previous work (González-García et al., 2021). The rotation systems without lupin cultivation are: *i*) CR1: Gc-WW → OSR; *ii*) CR2: Gc-WW → PT; *iii*) CR3: Gc-WW → MZ.

Table 1
Crop rotation sequences of rotation systems under organic and conventional regimen.

<table>
<tr><th>Rotation</th><th colspan="2">Year 1</th><th colspan="2">Year 2</th><th colspan="2">Year 3</th><th colspan="2">Year 4</th><th colspan="2">Year 5</th><th colspan="2">Year 6</th></tr>
<tr><td>RC1</td><td colspan="2">Gc-WW</td><td colspan="2">OSR</td><td colspan="2">Gc-WW</td><td colspan="2">OSR</td><td colspan="2">Gc-WW</td><td colspan="2">OSR</td></tr>
<tr><td>OA1</td><td colspan="2">Ge-WW</td><td colspan="2">OSR</td><td colspan="2">LPN</td><td colspan="2">Ge-WW</td><td colspan="2">OSR</td><td colspan="2">LPN</td></tr>
<tr><td>CR2</td><td colspan="2">Gc-WW</td><td colspan="2">Gc-WW</td><td colspan="2">PT</td><td colspan="2">Gc-WW</td><td colspan="2">Gc-WW</td><td colspan="2">PT</td></tr>
<tr><td>OA2</td><td colspan="2">LPN</td><td colspan="2">PT</td><td colspan="2">Ge-WW</td><td colspan="2">LPN</td><td colspan="2">PT</td><td colspan="2">Ge-WW</td></tr>
<tr><td>CR3</td><td colspan="2">Gc-WW</td><td colspan="2">MZ</td><td colspan="2">Gc-WW</td><td colspan="2">MZ</td><td colspan="2">Gc-WW</td><td colspan="2">MZ</td></tr>
<tr><td>OA3</td><td colspan="2">LPN</td><td>Ge-WW</td><td>OSR-G</td><td>OSR-G</td><td>MZ</td><td colspan="2">LPN</td><td>Ge-WW</td><td>OSR-G</td><td>OSR-G</td><td>MZ</td></tr>
</table>

Therefore, the comparison between rotation systems is as follows: *a*) CR1 – OA1; *b*) CR2 – OA2; and *c*) CR3 – OA3. The sequence of the rotation systems is presented in Table 1.

3. Results and discussion

The main objective of incorporating lupin is to improve the yield of the following crop in the rotation. Considering as a reference the yield of crops in a rotation without lupin (also in organic regime), wheat grain yield grows by about 12.5 % on average when it is the immediately following crop (i.e., OA1 and OA3: LPN → Ge-WW), and by about 7.5 % when it is the third crop in the rotation (i.e., OA2: LPN → PT → Ge-WW). Meanwhile, yield growth was around 12.5 % for PT, on average. Leaving the rapeseed biomass in the soil resulted in a yield increase of about 12.5 % for the MZ crop. A summary of the yield production is presented in Table A3 in the supplementary materials.

3.1. Environmental profiles based on land management

The comparison among the three rotation systems for the environmental impact categories under study is presented in Fig. 2. According to this figure, it is possible to observe that different rotation systems represent the best alternative based on the impact category evaluated. The OA1 system is the best option according to the indicators in six of the nine impact categories, such as TA, FE, TET, FET, MET and FRS. The most remarkable differences appear in FE and FRS categories in which OA1 represents a reduction of about 40 % and above 20 %, respectively, regarding OA2 and OA3 systems. The OA2 system is the alternative recommended only in the SOD category, but with a low difference of about 10 % with the rotation OA1. The OA3 system is the best rotation for GW and ME categories. In the first one, this rotation obtains differences about 46 % and 75 % with respect to rotation OA1 and OA3, respectively. Meanwhile, in the second one, environmental credits are obtained due to nitrogen fixation by lupin and maize crops. However, OA3 represents the worst option in SOD and TA categories, due to its higher emissions of dinitrogen monoxide and ammonia, respectively. Moreover, it is important to mention that the OA2 system is the worst performance in seven out of nine impact categories, such as GW, FE, ME, FRS, and toxicity-related categories. Although a reduced dose of insecticides and fungicides is applied along with the mechanical treatment in PT cultivation, this plays a key role in the remarkable difference in the toxicity-related categories.

Fig. 3 presents the crop contribution in each rotation in order to identify the crop that represent the hotspot of the system. In this sense, the identification of this crop depends on the impact category evaluated. In the OA1 system, the co-product OSR is the main contributor in GW, SOD and TA categories, due to field emissions by manure application. Meanwhile, lupin is the main contributor in toxicity-related categories (TET, FET, and MET) and marginally in FRS (about 7 % higher than Ge-WW). The seed and potassium-phosphate fertiliser production are behind these impacts. Furthermore, lupin presents the major copper and zinc emissions related to TET, as well as to FET and MET, respectively. The main crop Ge-WW is the major contributor only in the ME category, due to the nitrate emissions by foliar fertilisation.

In the OA2 system, potato plays a key role in the environmental impacts, being the main contributor in almost all categories evaluated, except for the FE category, where Ge-WW is the main contributor with 51 % of the

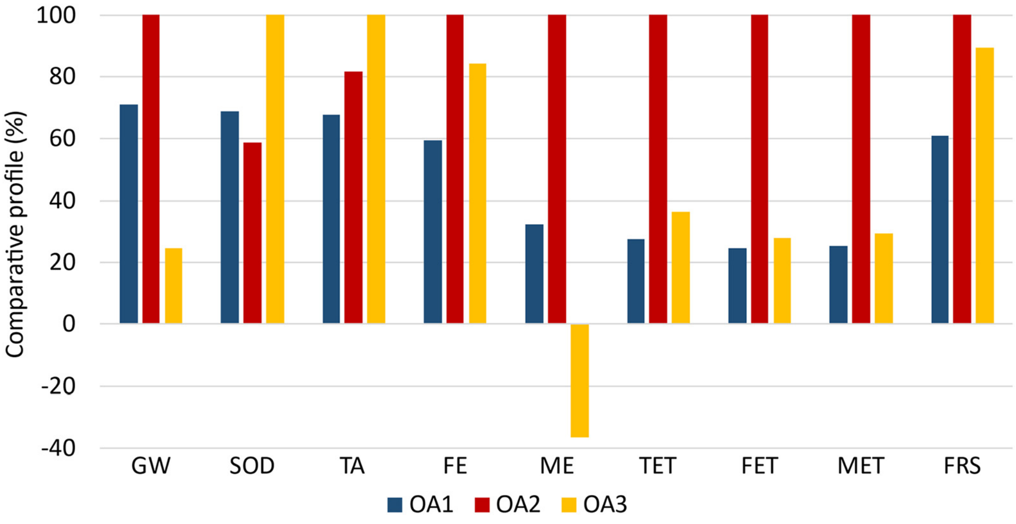


Fig. 2. Comparison of crop rotation systems based on land management (FU: 1 ha).

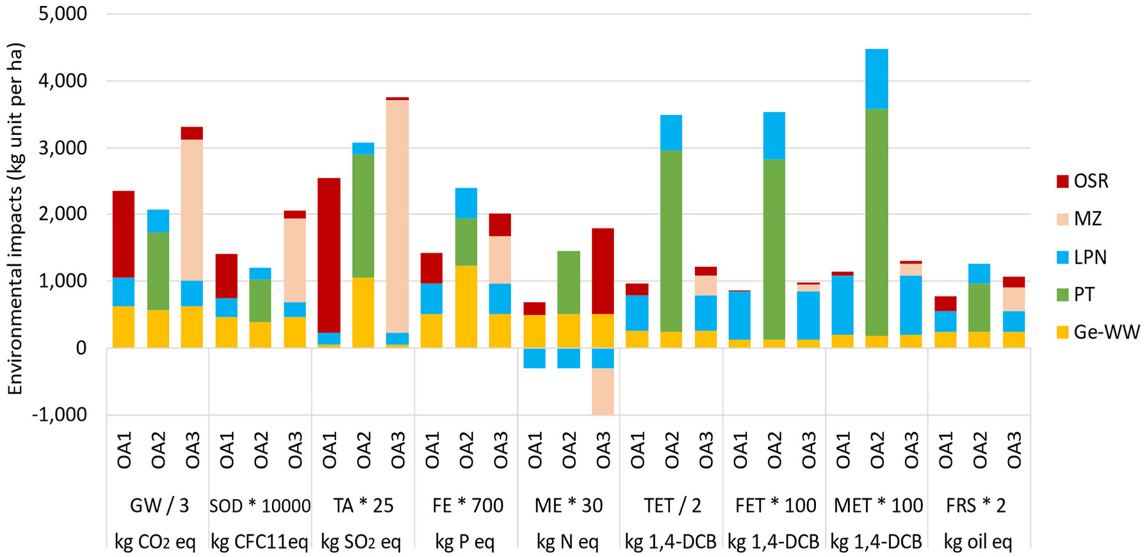


Fig. 3. Crops contribution in the rotation systems based on land management (FU: 1 ha).

impacts, due to phosphorus emissions. The contribution of potato is notably relevant in ME, by the nitrate emissions of poultry manure employment, as well as toxicity-related categories with a range of 76 % to 83 %. The production of seed and pesticide is the main responsible of toxicity impacts. Concerning the OA3 system, maize is the main contributor in five out of nine impact categories (GW, SOD, TA, FE, and FRS). This crop is the major consumer of diesel with about 96 $L{\cdot}h^{-1}$, which is almost twice the amount consumed by the other crops in the rotation and motivates its higher contribution to the FRS category. In GW category, the maize represents the 64 % of the impacts of the rotation, which is about three times the impacts of Ge-WW. The reason behind this is the field emissions by fertilisation, and the consequently, high dinitrogen monoxide emissions. Similarly, impacts related to SOD, TA, FE, are based on dinitrogen monoxide, ammonia, and phosphate field emissions, respectively. Exceptions occur in the eco-toxicity related categories, where lupin is the key crop. The rationale behind the main role of lupin in the toxicity-related categories lies in fertiliser production and seed production for planting activity. Moreover, lupin and maize in the OA3 systems represent environmental credits in ME category due to nitrogen fixation.

Fig. 4 shows the contribution of the life-cycle stage in the rotation systems in order to identify the relevant process in the environmental performance. Accordingly, field emissions represent the greatest contribution in five out of nine impact categories such as GW, SOD, TA, FE, and ME. Field emissions include emissions to air, water and soil associated with the fertiliser application and weed treatment (e.g., in PT and MZ crops), straw decomposition and the iLUC factor (289 kg CO_2eq per rotation system). Nitrogen-based fertilisation drives the relevant contribution of field emissions based on N_2O in the GW and SOD categories. Meanwhile, NH_3 is a relevant component in the TA category. Phosphate and nitrate emissions to water are the hotspots in the FE and ME categories respectively, arising from field emissions from fertilisers. For the toxicity-related categories, copper and zinc emissions are the main concerns, which occur due to machinery activities such as tillage and seeding, followed by fertiliser application. Moreover, in the FRS category, combined tillage, and sowing, followed by harvesting are the main responsible, mainly driven by crude oil consumption. Finally, a relevant factor in the GW category, contributing to reducing the GHG emission per cropping system, are the credits associated with the straw returned into the soil and the consequence increase in

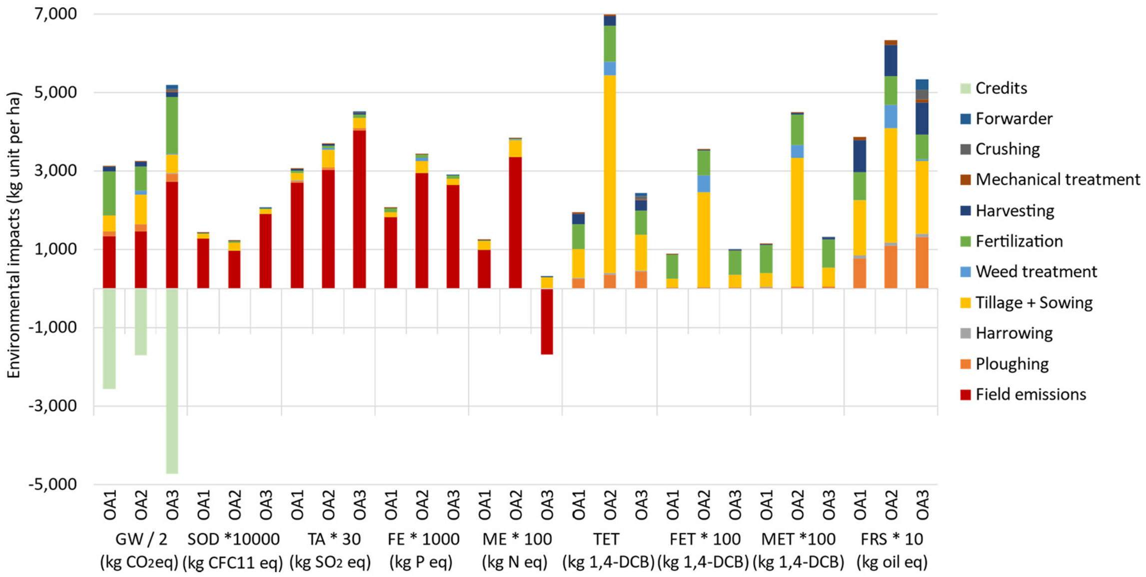


Fig. 4. Contribution of life-cycle stages in rotation systems based on land management.

the soil carbon content. This effect is noticeable in OA3 system because of the reception of large amounts of rapeseed straw. In this way, the carbon stored in the soil due to straw deposition are -5.1 t CO_2eq·ha^{-1} in OA1, -3.4 t CO_2eq·ha^{-1} in OA2, and $-$ 9.4 t CO_2eq·ha^{-1} in OA3 rotation. The lower contribution in OA2 system refers to that only the straw of wheat and lupine return to the field.

3.2. Environmental profiles based on economic performance

To determine the gross margin of the rotation systems, it is necessary to determine the income obtained from crop sales and the total costs involved. As for the total cost of production of rotation systems, this can be divided into activity costs (diesel, use of machinery and labour) and input costs (seeds, agrochemicals, fertilisers, and manure). Fig. A1 in Supplementary Materials depicts the contribution of income and costs of the main crop (i.e., Ge-WW) and alternative crops in the three cropping systems. Accordingly, OA2 system obtains the highest profit levels for this crop, and all three systems obtain a positive gross profit with 2985 €·ha^{-1} in OA1, 5708 €·ha^{-1} in OA2, and 4256 €·ha^{-1} in OA3.

Regarding the distribution of total costs, activity costs have the highest share in the rotation systems OA1 and OA3 with 66 % and 72 % of total costs, respectively. Meanwhile, input costs account for about 76 % of total costs in the OA2 system, due to the high value of seed inputs for potato cultivation. In addition, the costs associated with the production of alternative crops are quite remarkable. In this regard, alternative crops account for about 62 %, 89 % and 75 % of the total costs in system OA1, OA2 and OA3, respectively. However, alternate crops also represent the major sources of incomes in the rotation systems. Thus, these crops obtain a participation in the incomes of 63 % in OA1, 83 % in OA2, and 72 % in OA3. Those crops that obtain the major gross margin are OSR in OA1 (1070 €·ha^{-1}), PT in OA2 (3253 €·ha^{-1}) and MZ in OA3 (2860 €·ha^{-1}). Regarding the economic importance of lupin cultivation, this crop does not represent a relevant share of the total costs in the rotation systems, with contributions of 29 %, 8 % and 18 % in OA1, OA2 and OA3, respectively. Finally, concerning Ge-WW crop, the increase in the production yield by the introduction of lupin as predecessor crop lies in a growth of the gross margin of this cultivation.

Determining the environmental profiles per gross margin (€) (see Table 2), some changes in the preferences of the cropping systems are identified. The OA3 system is the recommended rotation in five of the nine categories, such as GW, ME, and toxicity. The OA2 system has the best environmental performance in the remaining four categories, such as SOD, TA, FE and FRS. The lowest benefit obtained by the OA1 system lies in the poor performance in eco-efficiency (environmental impacts for economic benefits), despite the best performance in five categories in the land management approach. In contrast, the shift in preference of the OA2 system is due to its higher benefit levels. However, this system still being the worst rotation in ME and toxicity-related categories. This also happen with the OA3 system, which improve the environmental performance in three categories (TET, FET, MET) with respect to the land management perspective, and it is marginally the worst option in SOD and TA categories. Finally, from an economic perspective, it is possible to establish that incorporate alternatives crops increase the profit of the rotation systems, improving their environmental performance.

Table 2

Environmental profile of organic rotation systems based on gross margin and protein-corrected grain.

Impact category	Unit	Gross margin (€)			Protein-corrected grain		
		OA1	OA2	OA3	OA1	OA2	OA3
GW	kg CO_2 eq	0.742	0.547	0.180	3.259	3.825	1.014
SOD	g CFC_{11} eq	0.047	0.021	0.048	0.208	0.148	0.272
TA	kg SO_2 eq	0.034	0.022	0.035	0.150	0.151	0.200
FE	g P eq	0.683	0.600	0.677	2.998	4.198	3.817
ME	g N eq	4.135	6.679	−3.257	18.164	46.749	−18.359
TET	kg 1,4-DCB	0.648	1.225	0.598	2.847	8.572	3.368
FET	kg 1,4-DCB	0.003	0.006	0.002	0.013	0.043	0.013
MET	kg 1,4-DCB	0.004	0.008	0.003	0.017	0.055	0.017
FRS	kg oil eq	0.129	0.111	0.133	0.569	0.776	0.750

3.3. Environmental profile based on grain protein content

Regarding the environmental profile of the rotation systems based on protein-corrected grain (see Table 2), the preferences of the rotation systems are similar to those obtained in the land management approach. The total amount of protein content obtained is 680, 815 and 755 kg·ha^{-1} in OA1, OA2 and OA3, respectively. OA1 system is the recommended system in six out of nine impact categories such as TA, FE, TET, FET, MET, and FRS. Meanwhile, the OA3 system is the best rotation in GW and ME categories, and the OA2 system is a feasible option only in SOD category. In this sense, the greatest amount of protein grain in OA2 system (815.4 kg) does not allow it to obtain a better environmental profile as occur in the economic perspective. Moreover, it is important to mention that the difference between the environmental profiles of OA1 and OA3 are lower in protein content perspective than land management. For example, in toxicity-related categories, the difference is 3 % considering the impacts based on the protein content, meanwhile, the difference is 5.4 % in the land management approach. Similarly, the results obtained for OA1 and OA2 in the TA category present a difference of about 1 %.

3.4. Comparing conventional and organic regimen

Under conventional conditions, the cultivation of the Galician variety is performed with few agricultural activities and low agrochemical requirements. As counterpart, organic regimen aims to minimize the inputs consumption and strictly limited the use of synthetic pesticides and mineral fertilisers. Here it is discussed and compared both agricultural regimes in order to determine benefits and drawbacks of the three organic rotation systems under study.

The comparative profile of the rotation systems based on land function is presented in Fig. 5. Accordingly, in almost all categories, the organic regimen presents the best environmental performance in the three rotation systems. The exception occurs in the TA category, in which all organic systems are worse than conventional regimen, mainly, due to the manure application as fertiliser. For example, the OA3 system reports the worst profile, due to the use of animal manure as fertiliser, mainly in maize crop (8 t·ha^{-1} of organic poultry manure and 15 m^3·ha^{-1} of organic cow manure). This motivates the outstanding field emissions of NH_3 into air (90 % of total contributing emissions). Regarding GW category, notable reductions are obtained with OA2 and OA3 regarding their conventional counterparts. The first one obtains a reduction of 93 % and the second one a 64 % regarding to CR2 and CR3, respectively. The role of the carbon storage in the soil when returning straw is applied allows to balance the GHG emissions produced by these rotations. CR1 returns about 28 t dry straw·ha^{-1} compared to the 19 t dry straw·ha^{-1} of the OA1. CR2 left in the field about 33 % more amount of dry straw than OA2 (9 against 6 t·ha^{-1}), and CR3 about 9 % more than OA3. However, if excluding the environmental benefits that this action represents, the three organic rotations are still better than conventional ones. OA1 system obtains a reduction of about 24 % with respect to CR1, meanwhile, OA2 and OA3 get a decrease of 34 % and 40 % relative to CR2 and CR3, respectively. In SOD category, the organic OA3 system obtains the highest reduction of about 40 % related to CR3. Furthermore, returning the biomass of LPN and OSR-G to soil allows the N fixation, which represents the benefits obtained in the OA3 system, and lies in a notable difference with CR3 in the ME category. In addition, organic systems get remarkable results in toxicity-related categories, as well as in FRS, especially in OA2 and O3 rotations. The above occurs due to the high consumption of fertilisers and agrochemicals in potato and maize cultivation in CR2 and CR3 systems, respectively.

If gross margin of organic and conventional regimens is compared (see Fig. 6a), introducing lupin in an organic regimen presents a close profit level in OA1 and OA2 systems with respect to conventional regimens CR1

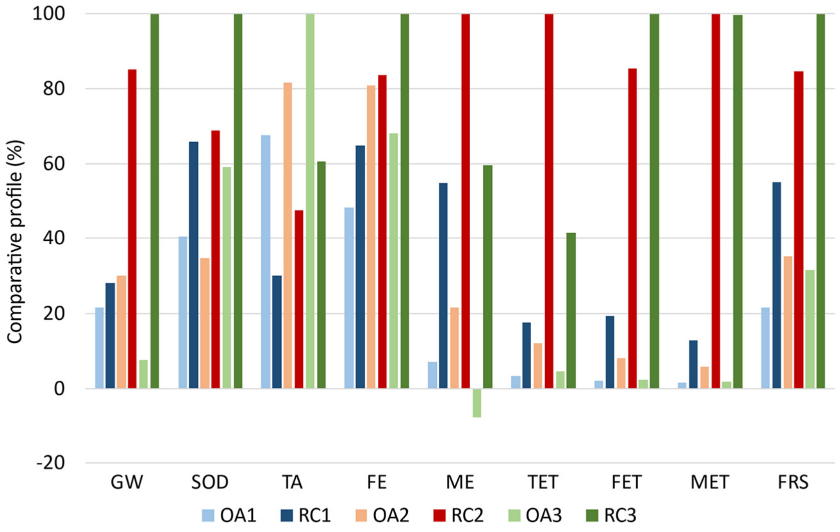
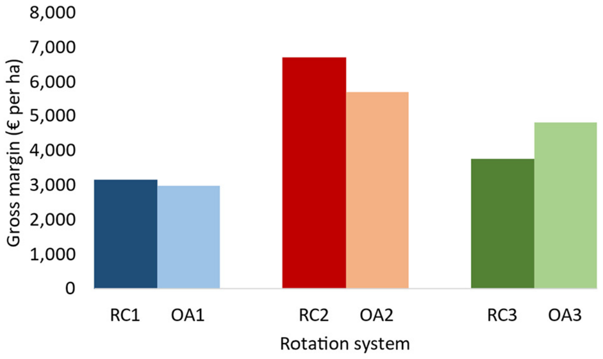
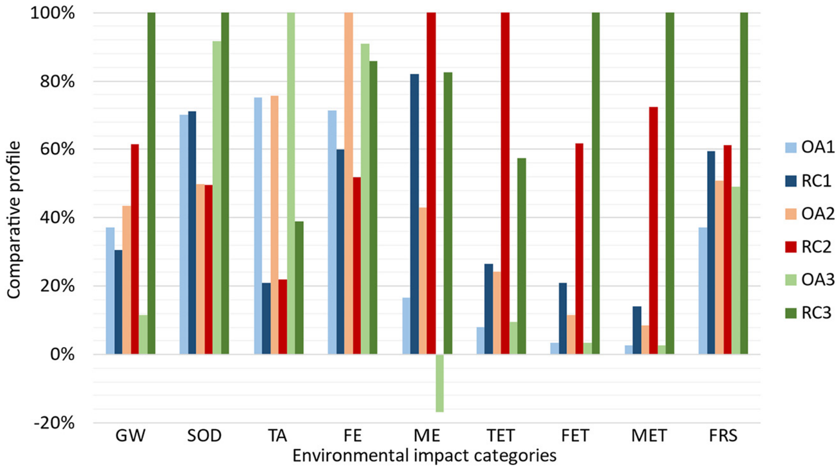


Fig. 5. Comparison of organic and conventional rotations based on land management.

and CR2, respectively. The OA1 system is only 6 % below the profit of the CR1 system (i.e., 191 €·ha^{-1}), meanwhile, the OA2 system is 15 % below the gross margin of CR2 (i.e., 991 €·ha^{-1}). The only one that obtains a higher profit level is the OA3 rotation, with about 28 % above than CR3 system (1053 €·ha^{-1}). In this sense, the introduction of lupin crop in these rotation systems support the growth of the yield production and, consequently, the profit level of the systems, obtained an economic performance closely to conventional regimen, and avoiding cost related to the consumption of agrochemicals. When the environmental impacts per gross margin are compared, results also indicate that organic rotations are the best alternative, apart for TA category (see Fig. A2 in Supplementary Materials). The highest reduction percentages are observed in ME and toxicity-related categories. Again, the use of agrochemicals is a vital factor in the environmental performance of these rotations.



a) Comparison of rotations based on margin gross



b) Comparison of rotations based on protein-corrected grain

Fig. 6. Comparison of rotation systems grain of organic and conventional rotations.

Since the introduction of the legumes in cereal rotation systems help to increase the protein content of the following crops (i.e., Ge-WW), both regimes are compare based on the protein performance. For the conventional systems, a protein content of 14.5 % is considered for Galician wheat grain (Campo Galego, 2020). The environmental performance of rotation systems under an organic regimen is better than conventional systems in various categories, such as GW, ME, TET, FET, MET and FRS (see Fig. 6b), despite the lower wheat yield production of organic regimen, which marginally rises due to the higher protein content because of lupin introduction. Exceptions occur in TA and FE categories in which conventional systems obtain better results, this happens because of the higher impacts related to ammonia emissions by manure fertilisation in organic systems in TA categories. Meanwhile, in the FE category, the higher yield quantity of grain produced in the conventional regimen allows for obtaining a lower profile of environmental impacts per protein content. Finally, in SOD category marginal reductions are obtained with organic rotations in OA1 and OA3, meanwhile, comparing rotation OA2 and CR2 no significant difference is observed.

4. Conclusions

This study aims to evaluate the environmental and economic implications of introducing lupin in three wheat-based rotation systems under an organic regimen in Galicia, Spain. Accordingly, the selection and implementation of the organic rotation system depends greatly in the type of co-products that will present in the lupin-wheat based rotation. In this sense, in terms of land management and protein content, the OA1 system is the recommend rotation in most of the impact evaluated, due to the lower impact contribution of rapeseed regarding potato or maize. Nevertheless, from an economic perspective, rotation OA3 is the best alternative since the higher gross margin obtained due to the co-products present in this rotation, mainly maize. Thus, farmers can select the alternative that suits best their main productive objective.

Results showed that, in general, the introduction of lupin crop represent a favourable strategy from an environmental and economic perspective. In this way, the application of nitrogen fertilisers could be reduced in the subsequent crops of the legume, leading to significant environmental improvements related to the reduction of field emissions, such as N_2O, NH_3 and nitrate leaching, among others, as well as less diesel consumption for related machinery activities. In this study, agricultural activities are important, for example to fossil resource scarcity, but not rather than fertilisation and their field emissions in the remaining categories. Furthermore, introducing lupin helps to increase the yield production of the following crop, leading in a higher profit level of the rotation.

On the other hand, organic rotations present, in general, a better environmental performance regarding conventional ones without lupin based on a land function. However, the higher NH_3 emissions from manure application is a challenge that requires further research to proposed lees impactful practices in this area. When focusing only on economic performance, lupin cultivation does not represent a relevant cost contribution and allows profit levels close to or even higher than conventional systems. Finally, this study provides useful information for farmers to support the implementation of viable strategies that represent environmental and economic benefits. Further studies could address the social performance of such systems in order to achieve sustainable agricultural systems.

CRediT authorship contribution statement

Ricardo Rebolledo-Leiva: Investigation, Methodology, Software, Writing – original draft preparation, Visualization. **Fernando Almeida-García**: data collection and reviewing. **Santiago Pereira-Lorenzo:** data collection and reviewing. **Benigno Ruíz-Nogueiras:** data collection and reviewing. **Maria Teresa Moreira:** Supervision, reviewing and editing. **Sara González-García**: Methodology, Supervision, Investigation, funding acquisition, reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research has been supported by the project Enhancing diversity in Mediterranean cereal farming systems (CerealMed) funded by PRIMA Programme and FEDER/Ministry of Science and Innovation–Spanish National Research Agency (PCI2020-111978) and by FEDER 2019/058A project in collaboration with Panaderia da Cunha. R.R.L., S.G.G. and M.T.M. belong to the Galician Competitive Research Groups (GRC)_ED431C-2021/37, co-funded by Xunta de Galicia and FEDER (EU).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157342.

References

Borghesi, G., Stefanini, R., Vignali, G., 2022. Life cycle assessment of packaged organic dairy product: a comparison of different methods for the environmental assessment of alternative scenarios. J. Food Eng. 318, 110902. https://doi.org/10.1016/j.jfoodeng.2021.110902.

Brandão, M., 2012. Food, Feed, Fuel, Timber or Carbon Sink? Towards Sustainable Land Use: A Consequential Life Cycle Approach. Cent. Environ. Strateg. Fac. Eng. Phys. Sci. Ph.D (PhD thesis).

Brankatschk, G., Finkbeiner, M., 2015. Modeling crop rotation in agricultural LCAs - challenges and potential solutions. Agric. Syst. 138, 66–76. https://doi.org/10.1016/j.agsy.2015.05.008.

CAAE, 2020. CERTIFICATE OF CONFORMITY OF EU INPUTS. CE-006795-2020. TIMAC AGRO ESPAÑA S.A.

Cai, S., Pittelkow, C.M., Zhao, X., Wang, S., 2018. Winter legume-rice rotations can reduce nitrogen pollution and carbon footprint while maintaining net ecosystem economic benefits. J. Clean. Prod. 195, 289–300. https://doi.org/10.1016/j.jclepro.2018.05.115.

Câmara-Salim, I., Almeida-García, F., González-García, S., Romero-Rodríguez, A., Ruíz-Nogueiras, B., Pereira-Lorenzo, S., Feijoo, G., Moreira, M.T., 2020. Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia,Spain. Sci. Total Environ. 713, 136720. https://doi.org/10.1016/j.scitotenv.2020.136720.

Câmara-Salim, I., Almeida-García, F., Feijoo, G., Moreira, M.T., González-García, S., 2021. Environmental consequences of wheat-based crop rotation in potato farming systems in GaliciaSpain. J. Environ. Manag. 287. https://doi.org/10.1016/j.jenvman.2021.112351.

Campo Galego, X.D.A., 2020. El trigo del país doblará su producción con la IGP Pan Galego [WWW Document]. URL https://www.campogalego.es/aumenta-la-produccion-de-trigo-autoctono-por-la-demanda-de-las-panaderias-que-apuestan-por-la-diferenciacion/.

<collab>Ministerio de Agricultura, P.y A.</collab>, 2021. Cereales [WWW Document]. URL https://www.mapa.gob.es/en/agricultura/temas/producciones-agricolas/cultivos-herbaceos/cereales/.

Cortés, A., Feijoo, G., Fernández, M., Moreira, M.T., 2021. Pursuing the route to eco-efficiency in dairy production: the case of Galician area. J. Clean. Prod. 285. https://doi.org/10.1016/j.jclepro.2020.124861.

EMEP/EEA, 2019. Air Pollutant Emission Inventory Guidebook 2019. Technical Guidance to Prepare National Emission Inventories. Appendix 3.D - Crop Production and Agricultural Soils, pp. 1–38.

Erice, G., Sanz-Sáez, Á., González-Torralba, J., Méndez-Espinoza, A.M., Urretavizcaya, I., Nieto, M.T., Serret, M.D., Araus, J.L., Irigoyen, J.J., Aranjuelo, I., 2019. Impact of elevated CO2 and drought on yield and quality traits of a historical (Blanqueta) and a modern (Sula) durum wheat. J. Cereal Sci. 87, 194–201. https://doi.org/10.1016/j.jcs.2019.03.012.

European Commission, 2018. Product Environmental Footprint Category Rules Guidance. PEFCR Guid. Doc. 238.

European Union, 2019. DECISIÓN DE EJECUCIÓN DE LA COMISIÓN de 16 de julio de 2019 relativa a la publicación en el Diario Oficial de la Unión Europea de la solicitud de registro de un nombre contemplada en el artículo 49 del Reglamento (UE) n.o 1151/2012 del Parlamento Europeo, pp. 3–8.

Faist Emmenegger, M., Reinhard, J., Zah, R., Ziep, T., 2009. Sustainability Quick Check for Biofuels - intermediate background report. Intermed. Backgr. report. Agroscope Reckenholz-Tänikon, Dübendorf, pp. 1–29.

Fang, Y., Singh, B.P., Cowie, A., Wang, W., Arachchi, M.H., Wang, H., Tavakkoli, E., 2019. Balancing nutrient stoichiometry facilitates the fate of wheat residue-carbon in physically defined soil organic matter fractions. Geoderma 354, 113883. https://doi.org/10.1016/j.geoderma.2019.113883.

Goglio, P., Grant, B.B., Smith, W.N., Desjardins, R.L., Worth, D.E., Zentner, R., Malhi, S.S., 2014. Impact of management strategies on the global warming potential at the cropping system level. Sci. Total Environ. 490, 921–933. https://doi.org/10.1016/j.scitotenv.2014.05.070.

Goglio, P., Brankatschk, G., Knudsen, M.T., Williams, A.G., Nemecek, T., 2018. Addressing crop interactions within cropping systems in LCA. Int. J. Life Cycle Assess. 23, 1735–1743. https://doi.org/10.1007/s11367-017-1393-9.

González-García, S., Gomez-Fernández, Z., Dias, A.C., Feijoo, G., Moreira, M.T., Arroja, L., 2014. Life cycle assessment of broiler chicken production: a Portuguese case study. J. Clean. Prod. 74, 125–134. https://doi.org/10.1016/j.jclepro.2014.03.067.

González-García, S., Almeida, F., Moreira, M.T., Brandão, M., 2021. Evaluating the environmental profiles of winter wheat rotation systems under different management strategies. Sci. Total Environ. 770. https://doi.org/10.1016/j.scitotenv.2021.145270.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

IPCC, 2019. N2O emissions from managed soils, and Co2 emissions from lime and urea application. 2019 Refinement to 2006 IPCC Guidel. Natl. Greenh. Gas Invent, pp. 1–48.

Iriarte, A., Yáñez, P., Villalobos, P., Huenchuleo, C., Rebolledo-Leiva, R., 2021. Carbon footprint of southern hemisphere fruit exported to Europe: the case of Chilean apple to the UK. J. Clean. Prod. 293. https://doi.org/10.1016/j.jclepro.2021.126118.

Köpke, U., Nemecek, T., 2010. Ecological services of faba bean. F. Crop. Res. 115, 217–233. https://doi.org/10.1016/j.fcr.2009.10.012.

Le Gouis, J., Oury, F.X., Charmet, G., 2020. How changes in climate and agricultural practices influenced wheat production in Western Europe. J. Cereal Sci. 93, 102960. https://doi.org/10.1016/j.jcs.2020.102960.

Liu, Q., Qiao, N., Xu, X., Xin, X., Han, J.Y., Tian, Y., Ouyang, H., Kuzyakov, Y., 2016. Nitrogen acquisition by plants and microorganisms in a temperate grassland. Sci. Rep. 6, 1–10. https://doi.org/10.1038/srep22642.

MacWilliam, S., Wismer, M., Kulshreshtha, S., 2014. Life cycle and economic assessment of Western Canadian pulse systems: the inclusion of pulses in crop rotations. Agric. Syst. 123, 43–53. https://doi.org/10.1016/j.agsy.2013.08.009.

Nemecek, T., Huguenin-Elie, O., Dubois, D., Gaillard, G., Schaller, B., Chervet, A., 2011. Life cycle assessment of Swiss farming systems: II.Extensive and intensive production. Agric. Syst. 104, 233–245. https://doi.org/10.1016/j.agsy.2010.07.007.

Nemecek, T., Hayer, F., Bonnin, E., Carrouée, B., Schneider, A., Vivier, C., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur. J. Agron. 65, 40–51. https://doi.org/10.1016/j.eja.2015.01.005.

van de Noort, M., 2016. Lupin: An Important Protein and Nutrient Source, Sustainable Protein Sources. Elsevier Inc. https://doi.org/10.1016/B978-0-12-802778-3.00010-X.

OECD, 2021. OECD/Food and Agriculture Organization of the United Nations (2021), “Cereals”. OECD-FAO Agricultural Outlook 2021-2030. OECD Publishing https://doi.org/10.1787/d494ca9a-en.

Pei, J., Li, H., Li, S., An, T., Farmer, J., Fu, S., Wang, J., 2015. Dynamics of maize carbon contribution to soil organic carbon in association with soil type and fertility level. PLoS One 10, 1–15. https://doi.org/10.1371/journal.pone.0120825.

Peterson, C.L., Hustrulid, T., 1998. Carbon cycle for rapeseed oil biodiesel fuels. Biomass Bioenergy 14, 91–101. https://doi.org/10.1016/S0961-9534(97)10028-9.

Popp, A., Lotze-Campen, H., Bodirsky, B., 2010. Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Glob. Environ. Chang. 20, 451–462. https://doi.org/10.1016/j.gloenvcha.2010.02.001.

Prasuhn, V., 2006. Erfassung der PO4-Austräge für die Ökobilanzierung - SALCA-Phosphor. Agroescope Reckenholz. 20.

PRé Consultants, 2020. SimaPro Database Manual - Methods Library. Methods Libr. PRé Consult, Amersfoort, Netherlands.

Prechsl, U.E., Wittwer, R., van der Heijden, M.G.A., Lüscher, G., Jeanneret, P., Nemecek, T., 2017. Assessing the environmental impacts of cropping systems and cover crops: life cycle assessment of FAST, a long-term arable farming field experiment. Agric. Syst. 157, 39–50. https://doi.org/10.1016/j.agsy.2017.06.011.

Rebolledo-Leiva, R., Almeida-García, F., Pereira-Lorenzo, S., Ruíz-Nogueira, B., Moreira, M.T., González-García, S., 2022. Introducing lupin in autochthonous wheat rotation systems in Galicia (NW Spain): an environmental and economic assessment. Sci. Total Environ. 838, 156016. https://doi.org/10.1016/j.scitotenv.2022.156016.

Schmidt, J., Weidema, B., Brandão, M., 2015. A framework for modelling indirect land use changes in life cycle assessment. J. Clean. Prod. 99, 230–238. https://doi.org/10.1016/j.jclepro.2015.03.013.

Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., De Snoo, G.R., Eden, P., 2001. Ecological impacts of arable intensification in Europe. J. Environ. Manag. 63, 337–365. https://doi.org/10.1006/jema.2001.0473.

Tizazu, H., Emire, S., 2010. Volume 10 No. 8 August 2010 chemical composition, physicochemical and functional properties of lupin. Afr. J. Food Agric. Nutr. Dev. 10, 3029–3046.

Vásquez-Ibarra, L., Iriarte, A., Rebolledo-Leiva, R., Vásquez, M., Angulo-Meza, L., González-Araya, M.C., 2021a. Considering the influence of the variability in management practices on the environmental impacts of fruit production: a case study on raspberry production in Chile. J. Clean. Prod. 313. https://doi.org/10.1016/j.jclepro.2021.127609.

Vásquez-Ibarra, L., Iriarte, A., Villalobos, P., Meza, F., Rebolledo-leiva, R., Angulo-meza, L., González, M.C., Iriarte, A., Villalobos, P., Meza, F., Rebolledo-leiva, R., Angulo-meza, L., A, M.C.G., Vásquez-ibarra, L., Rebolledo-leiva, R., 2021. A wide environmental analysis of beekeeping systems through life cycle assessment : key contributing activities and influence of operation scale assessment: key contributing activities and influence of operation scale. Int. J. Agric. Sustain. 0, 1–16. https://doi.org/10.1080/14735903.2021.1984108.

Vitale, G., Mosna, D., Bottani, E., Montanari, R., Vignali, G., 2018. Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste. Sustain. Prod. Consum. 14, 105–121. https://doi.org/10.1016/j.spc.2018.02.001.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Wowra, K., Zeller, V., Schebek, L., 2021. Nitrogen in life cycle assessment (LCA) of agricultural crop production systems: comparative analysis of regionalization approaches. Sci. Total Environ. 763, 143009. https://doi.org/10.1016/j.scitotenv.2020.143009.