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Environmental and economic benefits of wheat and chickpea crop rotation in the Mediterranean region of Apulia (Italy)

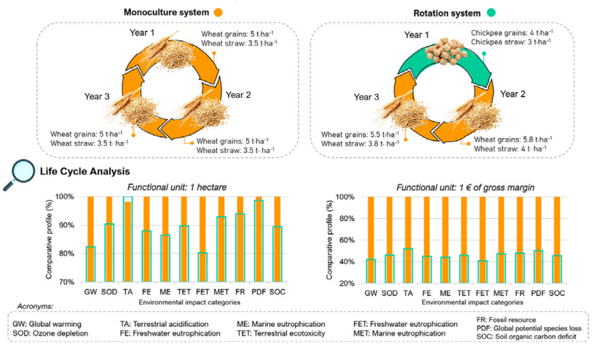
Sara Lago-Olveira [a,*], Ricardo Rebolledo-Leiva [a], Pasquale Garofalo [b], Maria Teresa Moreira [a], Sara González-García [a]

[a] *CRETUS, Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain*
[b] *Council for Agricultural Research and Economics, Research Center for Agriculture and Environment, Via Celso Ulpiani 5, 70125 Bari, Italy*

HIGHLIGHTS

- Chickpea-wheat rotation was evaluated and compared to traditional wheat monoculture.
- The rotation system provides environmental benefits compared to monoculture.
- The rotation system substantially improved soil quality.
- No significant differences in biodiversity loss were found between the two systems.
- The incorporation of chickpea resulted in a considerable increase in gross margin.

GRAPHICAL ABSTRACT



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ABSTRACT

Wheat plays an essential role in safeguarding global food security. However, its intensive agricultural production, aimed at maximizing crop yields and associated economic benefits, jeopardizes many ecosystem services and the economic stability of farmers. Rotations with leguminous are recognized as a promising strategy in favor of sustainable agriculture. However, not all crop rotations are suitable for promoting sustainability and their implications on agricultural soil and crop quality should be carefully analyzed. This research aims to demonstrate the environmental and economic benefits of introducing chickpea into a wheat-based system under Mediterranean pedo-climatic conditions. For this purpose, the crop rotation "wheat-chickpea" was evaluated and compared with the conventional regime (wheat monoculture) by means of life cycle assessment methodology. For this purpose, inventory data (e.g., agrochemical doses, machinery, energy consumption, production yield, among others) was compiled for each crop and cropping system, thus converted into environmental impacts based on two functional units: 1 ha per year and one € of gross margin. Eleven environmental indicators were analyzed, including soil quality and biodiversity loss. Results indicate that chickpea-wheat rotation system offers lower environmental impacts, regardless of the functional unit considered. Global warming (18 %) and freshwater ecotoxicity (20 %) were the categories with the largest reductions. Furthermore, a remarkable increase (96 %) in gross margin was observed with the rotation system, due to the low cost of chickpea cultivation and its higher market price. Nevertheless, proper fertilizer management remains essential to fully attain the environmental benefits of crop rotation with legumes.

1. Introduction

Wheat is one of the most widely grown and consumed cereals in the world (Erenstein et al., 2022). It provides up to 20 % of the population's

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* Corresponding author.
E-mail address: saralago.olveira@usc.es (S. Lago-Olveira).

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dietary calories and proteins, apart from being a rich source of micronutrients such as vitamins, and minerals (Poole et al., 2021), as well as bioactive compounds like fiber, polyphenols, and carotenoids (Luthria et al., 2015; Zingale et al., 2023).

According to the Food and Agriculture Organization of the United Nations (FAO), 761 million tons of wheat were produced worldwide in 2020, with Europe being the second largest producer area after Asia (representing a production share of 34 % and 46 %, respectively; FAO, 2022). Due to its several end-use products (e.g., pasta, bulgur, bread, couscous), this cash crop has considerable commercial importance. Only in Europe, wheat generated 45.1 billion euros of gross product value in 2020, which accounted for 9 % of the total gross production of the agricultural sector (FAO, 2022). In terms of varieties, durum wheat (*Triticum turgidum* L. ssp. *durum*) contains fewer but larger grains than bread wheat (*Triticum aestivum* L.) (Calderini et al., 2006). Although bread wheat is widely sown around the world, durum wheat (*Triticum turgidum* L. ssp. *durum*) can grow in more restricted agricultural areas like the Mediterranean region, which accounts for more than 50 % of the world's cultivated area (Marti and Slafer, 2014). The Mediterranean region has water and high-temperature stresses occurring mainly at the end of the growing season (Acevedo et al., 1999). Therefore, it is common to grow durum wheat in lower-yielding conditions, as it is considered more suitable for stressed environments than bread wheat due to its high level of tolerance to terminal drought (Monneveux et al., 2012). Consequently, durum wheat could be a crucial crop for global food security (Erenstein et al., 2022).

Since the second half of the century, wheat cultivation has been characterized for being an intensive production system aimed at maximizing crop yield and achieving high economic benefits (Muhammed et al., 2018). However, the application of high amount of fertilizers leads to nutrient leaching to groundwater and surface water, as well as greenhouse gas (GHG) emissions to the atmosphere, mainly in form of nitrogen dioxide, ammonia and nitrous oxide (Rose et al., 2023). With tillage, soil structure can be negatively altered, favoring the release of nutrients and carbon stored in the agricultural soil (Haddaway et al., 2017). In addition, the use of agrochemicals (herbicides, fungicides, insecticides) contaminates water sources and is harmful to non-target species that are in contact with these compounds, such as many insect and bird species (Sethi et al., 2022). Overall, these practices are driving a critical decline in the biodiversity pool, as well as disrupting ecosystem functions and services, including climate regulation, pollination services, biological control of weed and diseases, biomass production, clean water provision and soil formation (Palm et al., 2014; Tang et al., 2018). For wheat biodiversity in particular, issues such as the loss of traditional farming systems, migration of rural populations to cities and environmental degradation have led to the extinction of many local wheat varieties, where most of the unique cereal biodiversity has disappeared in the last century (Jaradat, 2013).

Although intensive f arming is aimed at improving the crop productivity, monoculture decreases wheat yield and negatively affects grain quality, including wet gluten content, volumetric weight, uniformity, and total ash content (Almeida-García et al., 2022; Woźniak, 2019). To compensate for the loss in performance farmers need to add mineral fertilizers and other agrochemicals, a practice that is increasingly intensifying over time to keep yield constant (Preissel et al., 2017; Rose et al., 2023). The heavy reliance on chemical inputs not only represents a significant share of production costs but can also pose a risk to farmer profits, as fertilizers prices are subjected to fluctuations due to external socioeconomic factors such as economic crises or geopolitical conflicts (Abbott and Borot de Battisti, 2011; IFPRI, 2022). Furthermore, due to the negative impacts of agrochemicals on the environment and human health, the European Commission (2017) is implementing new binding measures to reduce the use of chemicals up to 50 % by 2030. The new Directive, which replaces the Directive 2009/128/EC on the sustainable use of pesticides, encourages the adoption of alternative, eco-friendly methods of pest and weed control that do not rely on chemical foundations. Under these measures, it is essential to explore alternative approaches that promote sustainable and resilient food production systems in a context of increasing demand for agri-food products due to population growth and global challenges such as climate change (van Dijk et al., 2021).

A key role could be played by conservation agriculture (CA), which is gaining more and more acceptance in recent years, especially within organic and low-input farming systems. CA relied on three main agronomic principles: i) minimum soil tillage; ii) permanent organic soil cover and; iii) diversification of cropped species (Corsi and Muminjanov, 2019). CA in addition to other eco-friendly agricultural practices (i.e. growing stress-tolerant crop varieties and efficient use of resources) is recognized as providing sustainable and economically viable production system (Hoque et al., 2023).

Among the abovementioned principles of CA, crop rotation leads to improved soil health, alleviating weed and pest pressure (EIP-AGRI, 2020), providing significant fuel and agrochemicals costs savings (Preissel et al., 2017). Moreover, incorporating legumes reduces fertilizer requirement thanks to nitrogen atmospheric fixation which returns to the crop in rotation with legumes (Köpke and Nemecek, 2010). From a nutritional perspective, legumes are a source of protein and mineral nutrients (Stagnari et al., 2017) and are an important food source in Mediterranean diet (Cambeses-Franco et al., 2022). However, only 30 % of the legumes consumed in Europe are cultivated in this area, accounting for 1.5 % of European arable land (Costa et al., 2020).

Since the environmental performance of rotation systems can vary depending on several factors, including the specific species (Nemecek et al., 2015), the pedoclimatic conditions (Zingale et al., 2022) and the regimes under which such species are grown (Nemecek et al., 2015), it is necessary to assess the sustainability of each crop rotation, and identify the possible trade-offs between environmental burdens and productivity (Nemecek et al., 2015). In this regard, Life Cycle Assessment (LCA) methodology has proven to be a valuable tool for assessing multiple environmental impacts along the entire life cycle of the cropping system (Ahmad et al., 2023; Costa et al., 2020; González-García et al., 2021). The present manuscript aims to evaluate the environmental and economic performance of the wheat-chickpea rotation system grown in Southern Italy and to account for trade-offs and upstream effects resulting from the introduction of chickpea in rotation with durum wheat. To do this, the wheat-chickpea rotation system is compared with a durum wheat monoculture system. Different studies have been focused on the environmental performance of wheat grown under rotational regimes (González-García et al., 2021; Rebolledo-Leiva et al., 2022a, 2022b; Saeed et al., 2022). Nevertheless, no research articles were found that evaluated the environmental burdens of introducing chickpea into a wheat-based rotation system. Results from this investigation could: i) provide useful information for improving the environmental impacts of durum wheat cultivation under the investigated area and similar Mediterranean contexts; and ii) contribute to the achievement of the key environmental objectives framed within the European Green Deal and the Sustainable Development Goals (SDGs).

2. Material and methods

The attributional life cycle assessment methodology has been applied to conduct the environmental analysis of the agricultural systems discussed above. The analysis covers the main stages established by ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b), namely: i) goal and scope definition; ii) inventory analysis; iii) impact assessment and; iv) interpretation of the results, which are detailed in the following sections.

2.1. Goal and scope definition

The systems are located in the province of Foggia, in the Apulia region (Southern Italy; 41° 27′ 42.3″ N, 15° 32′ 42.1″ E), which is a leading producer of durum wheat in Italy, accounting for 23 % of the total Italian production (ISMEA Mercati, 2021). Apulia is characterized by the Mediterranean climate, with an average annual rainfall regime of 500 mm. The soils of this area are mainly Typic Calcixerets, a subtype of Vertisols of alluvial origin that are associated with calcareous parent materials with high clay content (40 %) and alkaline pH (8.3). As farmers are able to adapt to the pedoclimatic conditions of the region by practicing extensive farming without irrigation, they have a long tradition of growing durum wheat in the area. The area under study covers 4000 ha and has been cultivated with durum wheat for more than 30 years.

The system boundaries are drawn by the *cradle to farm-gate* approach (Fig. 1). This approach comprises the energy and material fluxes from the extraction of raw materials (e.g., fuel and minerals), inputs production and manufacturing (e.g., seeds, fertilizers, other agrochemicals, and agricultural equipment), machinery operation at field (with its related exhaust pipe and tire wear emissions), and machinery maintenance and end-of-life management to the crop harvesting.

2.2. Description of the agricultural systems

The agricultural systems are arranged in three-year growing seasons. In the case of monoculture system (W-W-W), winter wheat (*Triticum durum* L.) is grown every year from November to June, whereas in rotation (C-W-W), chickpea (*Cicer arietinum* L.) is cultivated instead of wheat at the beginning of each three-year agricultural system (year 1; Fig. 2).

Although wheat is the main commercial product, both crops are sold in the market. In the case of wheat, the grains are marketed for pasta production and straw for animal fodder. As for chickpea grains, they are destined for direct human consumption.

The crops are cultivated under minimum tillage practice and a rain-fed regime. Crop management involves a series of operations from seedbed preparation to harvest. Firstly, seedbed preparation corresponds to a shredding of the residual biomass left in the field from the previous crop, followed by fertilization and tillage operations for promoting nutrient uptake by roots, facilitating root expansion and limiting weed competition and pest spread and so on. These operations are carried out between September and November, after which the crop is sown. In the crop growth stage, emergence chemicals are applied to the field to prevent the development of weeds; nitrogen fertilizer as top dressing is provided in the first half of March. The growing season ends with seed harvesting and straw is left on the soil. The environmental loads and credits are allocated to each crop whose growing season begins after the harvest of the previous crop and ends with the harvest of the current crop (as explained in the next section).

2.2.1. Durum wheat management

Crop management begins in the first half of September shredding the straw left in the soil by the previous crop. Pre-sowing fertilization is performed by spreading mineral nitrogen fertilizer (di-ammonium phosphate (DAP) 18-46-0), providing to crops 36 kg N·ha^{-1} and 92 kg P·ha^{-1}, followed by the minimum tillage of soil at 0–20 cm depth by means of a rotary tiller. After seedling with 180 kg seed·ha^{-1} in December, herbicide and weed treatments are carried out to keep the soil clean from undesirable organisms. Herbicide treatment involves the combination of Atlantis® (metsulfuron-methyl 30 g·l^{-1} and iodosulfuron methyl-sodium 6 g·l^{-1}) at a concentration of 0.5 kg·ha^{-1} and 1 l·ha^{-1} of Biopower® surfactant adjuvant (sodium lauryl ether sulphate 27.65 % p/v). Weed treatment consists of 500 ml·ha^{-1} of Buctril® (bromoxynil and 2,4-D 225 g·l^{-1}). To support the crop grown, fertilization at top dressing is applied, consisting of 68.4 kg N·ha^{-1} of ammonium nitrate (AN) 34.2 % fertilizer. In June, seed yield is harvested by a combined machine. Regarding straw management, in the first year, all the straw biomass is left in the field. In the second year, only part of the straw is left in the soil (between 15 % and 20 %), while the rest is removed and sold for animal feeding. The selling price of wheat grain was set to 0.29 €·kg^{-1} and 0.07 €·kg^{-1} for straw. An overview of the agricultural practices involved in durum wheat management is given in Table S1 of the Supplementary material.

2.2.2. Chickpea cultivation procedure

As for durum wheat, chickpea cultivation begins in September shredding the straw left in the field after the harvest of the previous crop. Fertilization takes place in November supplying 54 kg N·ha^{-1} and 138 kg P·ha^{-1} as di-ammonium phosphate (DAP) 18-46-0 by a fertilizer spreader. A rotary tiller is used to practice the minimum tillage, followed by the sowing of 60–80 kg·ha^{-1} of chickpea seeds. After emergence the control of weed is performed by 1.25 l·ha^{-1} of Corum® (bentazone 480 g·l^{-1} and imazamox 2.24 % p/v.). To limit the diffusion of pests on the crop, chickpea is protected with 1 kg·ha^{-1} of Coprantol® 30 %, supplied in April. At the beginning of July, the harvest is performed by a combined machine, gathering between 3 and 5 t·ha^{-1} of chickpea on average (standard deviation: 1.6 t·ha^{-1}, median: 4.1 t·ha^{-1}), while the straw is left in the field (between 2 and 4 t·ha^{-1}). The selling price of chickpea seed is 0.9 €·kg^{-1}. An overview of the agricultural practices involved in chickpea management is provided in Table S2 of the Supplementary material. Furthermore, it is relevant to highlight that the management of wheat-chickpea rotation systems relied on the same soil-crop operations reported for the monoculture regimen.

2.3. Functional unit and allocation

To quantify the loads on environment of the agricultural systems here analyzed, it is necessary to define the functional unit (FU) selected. In this

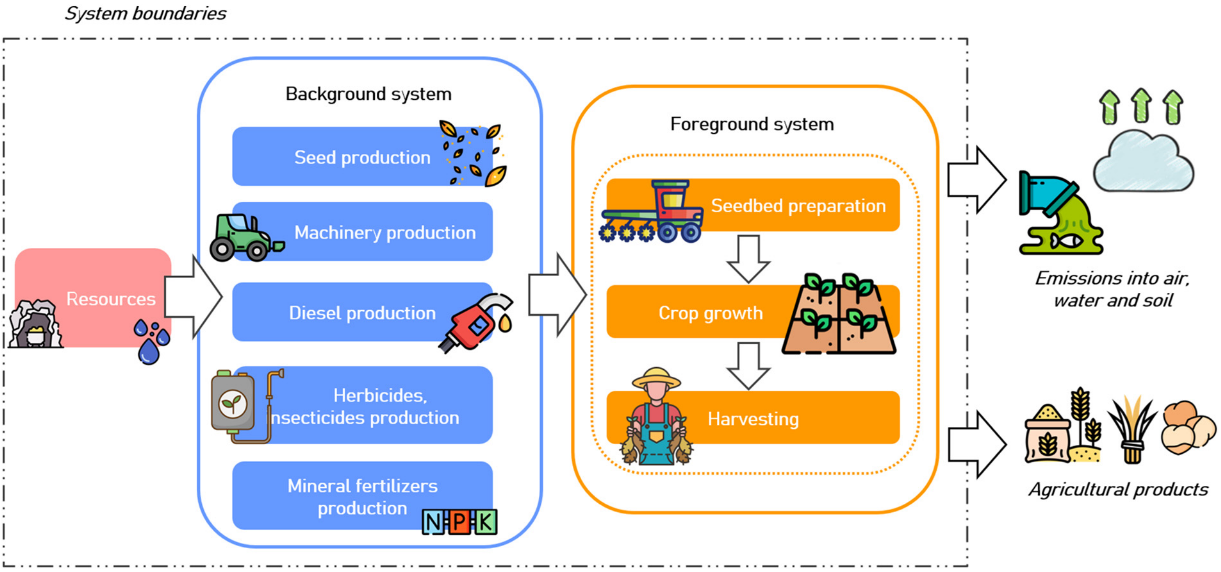

Fig. 1. System boundaries of the cropping systems under study within the *cradle to farm-gate* approach.

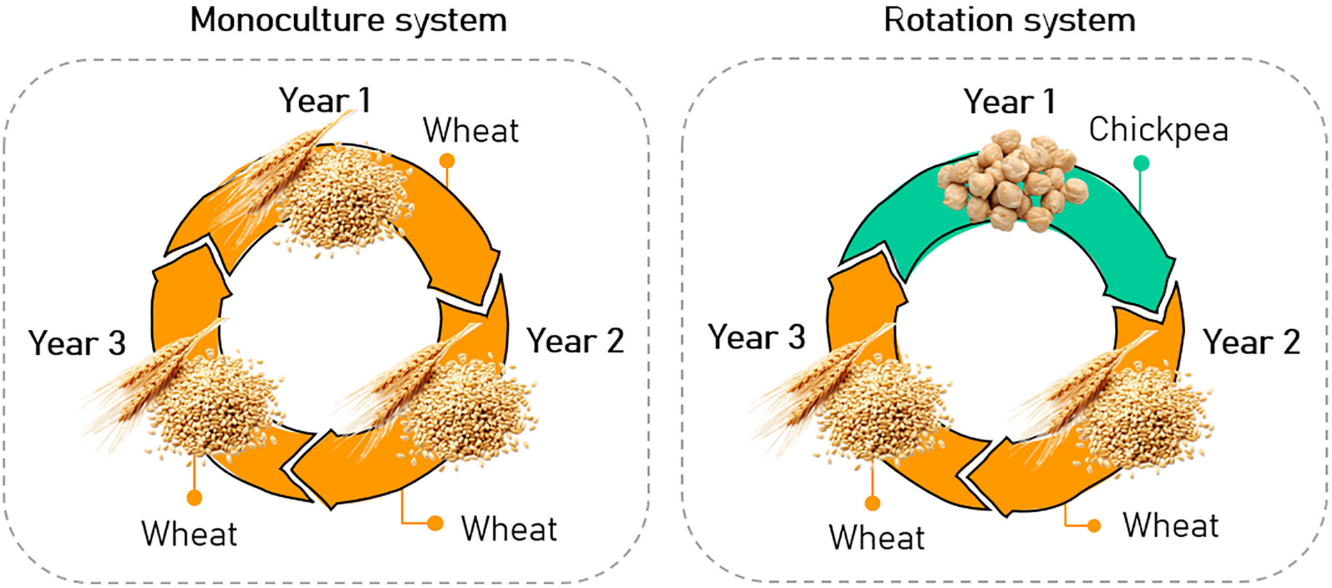

Fig. 2. Layout of the cropping systems under study. Average annual grain and straw production for each year and crop are shown. In brackets is the percentage of straw returned to the soil.

research, two FUs were selected. The first FU was 1 ha of cropped land per year (i.e., 1 ha·y) for raising the farmers' awareness of the environmental improvement when shifting from a conventional cropping system (wheat in monoculture) to a rotational one (wheat in rotation with legumes). In other words, how the environmental burdens could be improved through of land management.

An economic functional unit (one euro of gross margin) was defined as the second FU, based on the assumption that the main goal of farmers is to make profit from their work. Moreover, as the analysis and comparison between schemes were carried out at a system level (i.e., considering all products and by-products as a whole), no allocation method for distributing the burdens was needed.

2.4. Life cycle inventory

Life cycle inventory catalogs and quantifies the input and output flows throughout the life cycle of a product or system. Two types of data can be reported within the life cycle inventory: primary and secondary data.

Primary data were collected by questionnaire from the main agricultural cooperatives in the region involved in the production, purchase, and sale of durum wheat. The survey data include information from more than 100 farmers who rely on the cooperative to market their product. These farmers own about 50 % of the area under durum wheat (and chickpeas) (4000 ha). Statistical tests related to traditional indicators such as mean, standard deviation, and median values were considered in the analysis of the 100 farmers.

The secondary data were obtained from the Ecoinvent® database 3.9v (Wernet et al., 2016). Depending on the type of data used, two distinct systems can be identified. The foreground system is primary information related to the practices for crop cultivation and the background system corresponds to the extraction of raw materials, manufacturing of the agro-inputs and the corresponding environmental burdens and emissions from tire wear and exhaust pipe for their application by machinery on the field. To estimate the contribution of machine used for carrying out the cropping systems, the weight, time of operation and service life of each machine was taken into account. Other than collected data, further primary figures, such on-field emissions were estimated by several empirical models specific to this scientific field.

On-field emissions are those emissions to air, water and soil by agrochemicals (fertilizers, herbicides, insecticides) applied to crop/soil, application of agrochemicals (fertilizers, herbicides, insecticides), diesel combustion and land use change. Nitrous oxides (N_2O) emissions come out from the supply of N-based fertilizers and straw to soil. According to the Intergovernmental Panel on Climate Change (2019a), direct N_2O emissions were computed by using as emission factor the value of 0.010 kg N-N_2O per kg N to convert the nitrogen fraction of the straw and N-based fertilizers in N_2O.

Indirect N_2O emissions were calculated as the sum of N volatilization/deposition and N leaching. For the former, a conversion factor of 0.050 kg per kg N of ammonium was used. Moreover, the fraction of N deposited on soils and water was assessed with an emission factor of 0.010. For N_2O leaching, a factor of 0.240 kg per kg of N applied with fertilizer was used whereas 0.011 kg per kg of N leached was the conversion factor to estimate N-N_2O lost with N leaching. Nitrate (NO_3^-) leaching to groundwater was estimated by using the model of Faist et al. (2009). For modelling this emission, annual precipitation of 500 mm (iLMeteo, 2022), rooting depth of 1.20 m and 1.05 m for wheat and chickpea, respectively (Palta and Turner, 2019; Thomas et al., 2019), and soil clay content of 40 % were considered (Costantini and Dazzi, 2013). Nitrogen dioxide (NO_2) and ammonia (NH_3) emissions to the atmosphere from fertilization were quantified following the guidelines suggested by the European Environment Agency and the European Monitoring and Assessment Program (EMEP/EEA, 2019). Specifically, for NO_2, 0.040 kg NO_2·kg N^{-1} emission factor was applied and the conversion factors for counting NH_3 emission relied on soil pH (above 7), climate (warm) and type of fertilizer. On this basis, 94 and 33 g NH_3 kg N^{-1} coefficient factors were assumed when calculating the related DAP and AN emissions, respectively.

The share of phosphate loss due to fertilization was estimated following the SALCA-P model (Prasuhn, 2006). The conversion factor of 0.175 kg P·ha^{-1}·yr^{-1} per kg P·ha^{-1} supplied with fertilization was used for quantifying phosphate runoff to surface water, while the conversion factor of 0.07 kg P·ha^{-1}·yr^{-1} per kg P·ha^{-1} for phosphate leached from fertilizer into groundwater. Furthermore, the PEFCR protocol provides guidelines for calculating emissions related to plant protection products (European Commission, 2018). From plant protection, it was assumed that 1 % of the active ingredients ended up in the groundwater, 9 % in air and 90 % in the soil. Emission factors are summarized in Table S4 of the Supplementary material.

The land use changes (LUC) determine modifications in the soil carbon stock, this being the balance between gains and losses resulting from the different agricultural practices. LUC can be split up into direct (dLUC) and indirect land-use change emissions (iLUC) (Schmidt et al., 2015). As regards dLUC, emissions are related to the soil on which the cropping systems are carried out. Conversely, iLUC refers to emissions associated with land use changes occurring elsewhere beyond the area analyzed due to crop displacements.

On the agricultural land, the straw left on the field recovers the soil carbon stock. However, only a share of this carbon stock remains in the field, improving the soil quality by acting on water retention, structure of aggregates, porosity, and so on. The carbon content of straw corresponds to 49 % and 42 % (dry biomass) for durum wheat and chickpea, respectively (Brandão et al., 2012; IPCC, 2019a; Nazari et al., 2019). From this total carbon content, only 16 % represents the recalcitrant form of organic carbon left in the soil (Fang et al., 2019), which was considered an environmental credit. The remaining fraction (84 %) is lost in the atmosphere as CO_2 emission. However, this environmental load is not accounted for since the balance between this CO_2 emission and atmospheric CO_2 subtracted by photosynthesis is deemed neutral (Rebolledo-Leiva et al., 2022b).

As regards iLUC, an estimation was obtained from the Schmidt et al. (2015) model following a seven-step procedure. Step 1: land requirement: 1 ha·yr was considered as the land per cropping system; Step 2 and 3: the potential net primary production (NPP_0) was 5.11 t C·ha^{-1}·yr^{-1} for Apulia region (e.g., amount of biomass produced by crops per unit land and year); Step 4: 6.11 t C·ha^{-1}·yr^{-1} as the average NPP_0 for arable land; Step 5: the relative productivity (0.84 pw ha·yr·ha^{-1}·yr^{-1}) was calculated by dividing NPP_0 of the region (5.11 t C·ha^{-1}·yr^{-1}) by the average (6.11 t C·ha^{-1}·yr^{-1}); Step 6: the previous results is used to convert the current land used (1 ha·yr) into units of productivity weighted hectare years (pw ha·yr). Step 7: the GHG emissions were estimated using the factor of 0.042 t CO_2 ·pw ha^{-1}·yr^{-1} for agricultural soils.

2.5. Life cycle impact assessment

The environmental performance of the cropping systems under investigation was assessed following the ReCiPe hierarchist midpoint method (V1.06) (Huijbregts et al., 2017). Specifically, nine ReCiPe midpoint impact categories were chosen because of their relevance and frequency of use in the context of rain-fed cropping systems (Costa et al., 2021; Zingale et al., 2022). These are global warming (GW), stratospheric ozone depletion (SOD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), and fossil resources (FR).

In addition, to obtain a wide perspective of the environmental performance of the rotation system, the global potential species loss (PDF) and the soil organic carbon (SOC) deficit were also evaluated, in line with the recommendation of UNEP-SETAC Life Cycle Initiative (2019). These two indicators measure the impact of land-use and land-transformation pressures on two key environmental areas: biodiversity and soil quality (PDF and SOC, respectively). To date, they have rarely been used in the scientific community, mainly due to the difficulties encountered in representing coherent and complete cause-effect chains (Life Cycle Initiative, 2016; UNEP-SETAC Life Cycle Initiative, 2019; Costa et al., 2020; Vidal-Legaz et al., 2016). On the one hand, PDF has been built on the field-species relationship (SAR) model developed by Chaudhary et al. (2015); Chaudhary and Brooks (2018). To assess the impact on a global scale, the regional species loss predicted by the SAR model was multiplied by vulnerability factors, which are a function of the endemic richness of the region studied and the level of threat to the species (Chaudhary et al., 2015). As this indicator measures the damage at the ecosystem level, it corresponds to an endpoint impact category. The SOC, on the other hand, is based on the model of Milà i Canals et al. (2007). The characterization factors used for the background system were those provided by Brandão and Canals (2013), while the characterization factors for the foreground processes were derived following the method of Brandão and Canals (2013) and considering the default parameters proposed by the IPCC (2019b) guidelines for climate (warm temperate), soils (clay) and crop management (long-term cultivation, reduced tillage and medium inputs). In this case, SOC is a midpoint impact category that assesses impacts on intermediate aspects located between inventory flows and endpoints (Vidal-Legaz et al., 2016). The environmental impact assessment was carried out using SimaPro v9.3 software (PRé Sustainability, 2022) and Microsoft Excel® 365 MSO.

2.6. Margin gross assessment

In line with González-García et al. (2021), the gross margin was quantified as the difference between the total incomes related to the sale of harvested products (wheat and chickpea grain and wheat straw), and the costs of inputs (seeds, fertilizers, and other agrochemicals), plus the cost to perform field operations (diesel, use of machinery, human labor). The source of economic data for the sale of wheat and chickpeas is the historical record of the weekly prices of the Chamber of Commerce of Foggia (last three growing seasons) (Chamber-Commerce, 2023), while the cost of agro-inputs was obtained from the information reported in the questionnaire administered to local cooperatives.

3. Results

3.1. Production yield

As mentioned above, the management of the rotation system was based on the same soil-crop operations as the monoculture. However, different yields were observed when the legume was introduced. The mean yield of wheat in continuous cropping system was considered equal to 5 t·ha^{-1} (standard deviation: 1.02 t·ha^{-1} and median 5.13 t·ha^{-1}), whereas that in the rotation was equal to 5.8 t·ha^{-1} and 5.5 t·ha^{-1} for the first and second growing seasons after chickpea cultivation, respectively. The improvement in wheat yield (16 % and 10 % in the second and third year of the rotation, respectively, compared to the monoculture regime) is consistent with similar rotation cropping systems reported in previous studies (Christen, 2001; Gan et al., 2015; Giles et al., 2009; Kirkegaard et al., 2008; Plaza-Bonilla et al., 2017; Rebolledo-Leiva et al., 2022b).

3.2. Environmental performance based on a land management functional unit

Introduction of chickpea (C-W-W) in rotation with durum wheat presents an overall environmental improvement compared to wheat grown in monoculture (W-W-W) (Fig. 3). GW and FET experience the highest burden reduction (18 % and 20 % respectively), followed, in decreasing order, by ME, FE, SOC, SOD, TET, MET and FR (from 13 % to 6 %). These reductions were mainly attributed to the lower fertilization applied to the rotation system.

In this sense, while the whole rotation system is supplied with 1100 kg·ha^{-1} of mineral fertilizer distributed in five passes (one pass per cultivation of chickpea and two passes per wheat), wheat monoculture receives 1200 kg·ha^{-1} of mineral fertilizer distributed in six passes. Besides fertilization, pest and weed control treatments also play a key role in terms of FET, since the application of Atlantis® and Buctril® agrochemicals during wheat cultivation represents 50 % and 41 % of overall FET burdens (in monoculture and rotation, respectively). As for SOC, the rotation system leads to a higher carbon supply than the monoculture because of its higher biomass production (Fig. 2), which ultimately results in better soil quality.

Concerning PDF, the introduction of chickpea provides a negligible improvement (1 %). The reason behind this result lies in the fact that PDF impact is almost entirely (99 %) caused by land use pressures occurring at the foreground system. Consequently, given that both cropping systems are grown in the same agricultural area (with the same species richness, level of vulnerability of the species and degree of conservation of the natural habitat), no significant difference is observed between both scenarios.

In contrast to the other impact categories, monoculture presents a more favorable environmental profile in terms of TA (81 and 83 kg SO_2 eq, respectively). This result is a consequence of the higher amount of DAP fertilizer applied to the chickpea crop (a total of 700 kg·ha^{-1} to C-W-W and 600 kg·ha^{-1} to W-W-W), whose manufacturing process proved to offer a higher contribution to TA impact than the other fertilizers. The impact

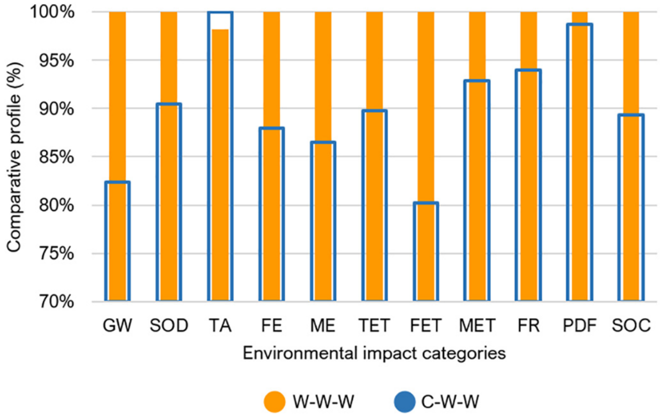

Fig. 3. Comparison of environmental profiles of monoculture (W-W-W) and rotation (C-W-W) systems per hectare (GW: Global warming, SOD: Ozone depletion, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TET: Terrestrial ecotoxicity, FET: Freshwater eutrophication, MET: Marine eutrophication, FR: Fossil resource, PDF: Global potential species loss, SOC: Soil organic carbon deficit).

values for all impact categories and scenarios can be found in Table S5 of the Supplementary material.

The contribution of each crop to the overall environmental impact of the rotation system is depicted in Fig. 4. The chickpea crop is notable for its lower contribution in most impact categories, accounting for between 17 % and 29 % of the total environmental loads produced by the rotation. Its better performance is mainly attributed to its lower fertilization requirement compared to durum wheat cultivation.

In line with the results presented above, TA, PDF and SOC are the only categories for which chickpea shares a similar impact contribution as its wheat counterparts (PDF, SOC) or even exceeds them by 5 % (TA).

Wheat cultivation entails the same environmental burdens for almost all impact categories, regardless of whether it is grown after chickpea (wheat of year 2) or wheat (wheat of year 3). This is explained by the fact that the same operations and inputs are applied in both years, with the only exception being the amount of straw they received from the previous crop. While in the second year wheat receives 100 % of the straw produced by the chickpea (3000 kg·ha^{-1}), in the third year the crop only receives 15 % to 20 % of the straw produced by the preceding wheat (700 kg·ha^{-1}). Such a difference in straw input leads to some variations in GW and SOD profiles. In the case of GW, returning straw to the field has the advantage of avoiding CO_2 emissions to the atmosphere (due to carbon storage in the soil), although in return, it releases N_2O as it decomposes. The trade-off results in negative net CO_2 emissions and thus a lower GW load (24 % lower) from wheat with higher straw input. However, as far as SOD is concerned, only N_2O emissions are considered. Thus, wheat grown in the third year shows a slightly better performance, with 6 % less load compared to wheat grown in the previous year. Similar results were observed in Rebolledo-Leiva et al. (2022b, 2022a). Regarding the monoculture system, no environmental differences are identified between the three wheat growing periods, as the same activities and agricultural inputs are used consistently, regardless of the year.

3.3. Hotspot analysis contributing to environmental burdens

Focusing on the specific factors that shape the environmental profile of the agricultural systems (Fig. 5), the on-field emissions contribute the most weight in most impact categories, accounting for emissions to air, soil and water from the application of agrochemicals (fertilizers, insecticides and herbicides), straw decomposition and iLUC (35 kg CO_2 eq per agricultural system).

The impact categories most influenced by emissions in the field (89 % to 97 %) are ME and SOD, followed by FE (60 %). The main emissions concerned are NO_3^- for ME, N_2O for SOD, and phosphate in the case of FE. NO_3^- emissions are attributed to the application of mineral N-fertilizers, while N_2O emissions are due not only to N-fertilizers but also to straw decomposition processes, although to a lesser extent.

As for phosphate emissions, they occur due to the application of phosphate fertilizers. In addition, GW, TA and FET are also considerably affected by the on-field emissions, ranging from 29 % to 52 % depending on the impact category and the system considered.

In the case of GW, this is a consequence of N-fertilizer application and straw decomposition, which contribute GHG emissions (N_2O) to the atmosphere; while in the case of TA, NH_3 emissions associated with fertilization are responsible for the loads associated with on-field emissions. On the other hand, FET is due to emissions of metsulfuron, an active ingredient found in the herbicide Atlantis®.

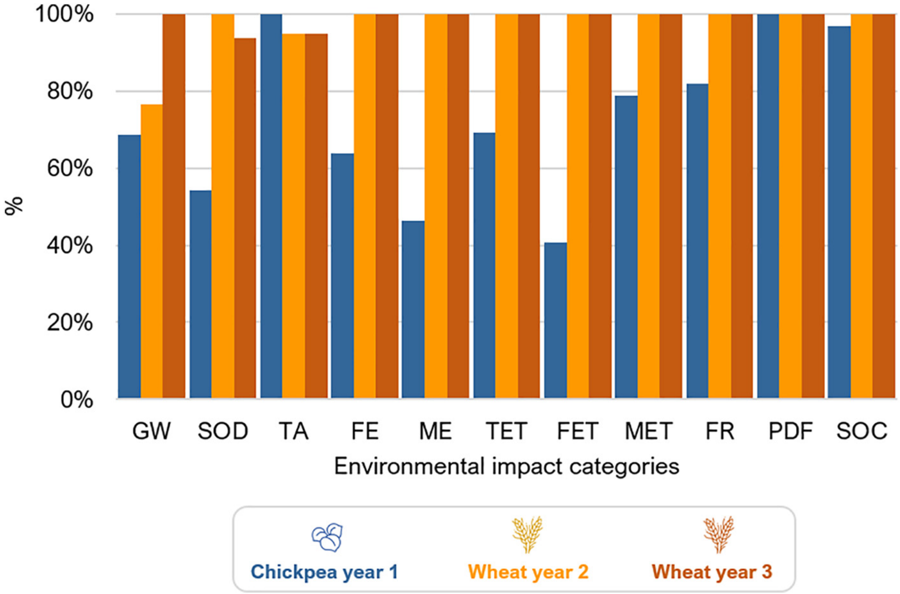

Fig. 4. Crop contribution (%) to the overall environmental profile of the rotation system related to 1 ha (GW: Global warming, SOD: Ozone depletion, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TET: Terrestrial ecotoxicity, FET: Freshwater eutrophication, MET: Marine eutrophication, FR: Fossil resource, PDF: Global potential species loss, SOC: Soil organic carbon deficit).

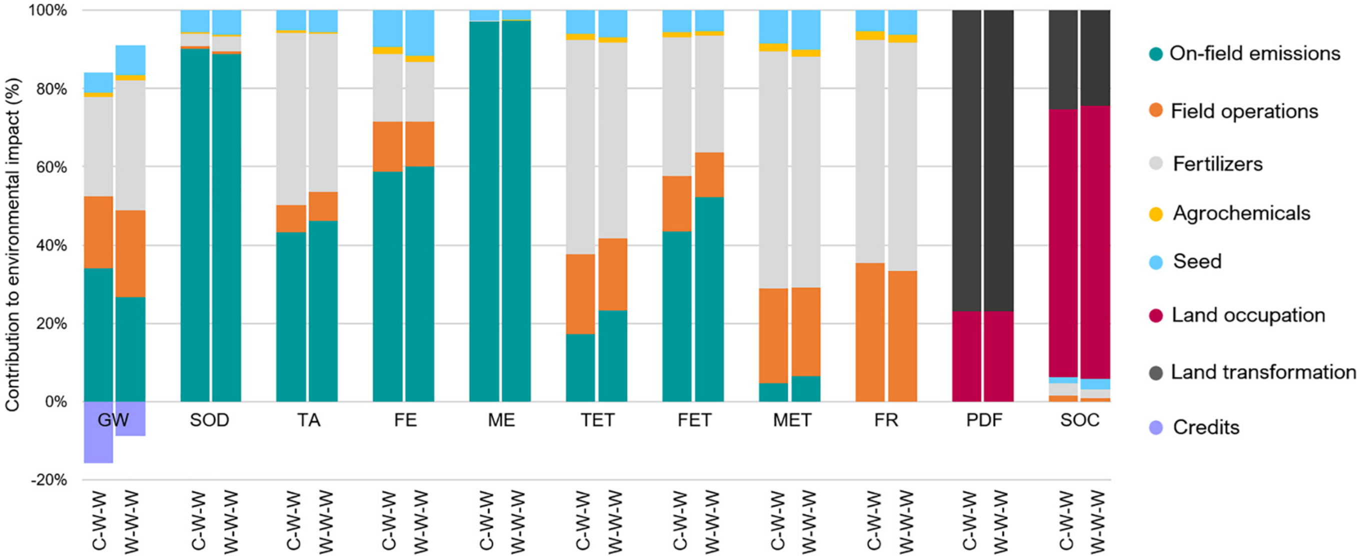

Fig. 5. Distribution of environmental impacts per cropping systems across affected parameters. (C-W-W: rotation system, W-W-W: monoculture system, GW: Global warming, SOD: Ozone depletion, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TET: Terrestrial ecotoxicity, FET: Freshwater eutrophication, MET: Marine eutrophication, FR: Fossil resource, PDF: Global potential species loss, SOC: Soil organic carbon deficit).

Fertilizer manufacturing is the second most important factor affecting the environmental burdens after fertilizer application on field. This parameter mainly accounts for MET, TET and FR (from 50 % to 61 %), and to a lesser extent, for TA, FET and GW (from 30 % to 44 %). Firstly, the extraction of the raw materials needed to produce the fertilizer involves the discharge of several metals (copper, zinc and nickel) to water, ultimately contributing to the MET, TET and FET impacts. Secondly, the manufacturing processes consume a considerable amount of natural gas which combustion generates SO_2 and CO_2 emissions, playing a main role in TA and GW profiles, respectively. Furthermore, FR is also being affected by the use of fossil resources.

As regards field operations, their contribution is noteworthy in FR, GW, TET, and MET, ranging from 18 % to 35 % depending on the agricultural system and the impact category considered. As for fertilizer manufacturing, the machinery used in field operations requires fossil fuels. Therefore, these processes contribute to GW due to CO_2 emissions released during combustion and FR due to the depletion of fossil resources. Moreover, machinery manufacturing delivers various metals to the air (copper, zinc and nickel), which influences TET and MET impact categories. Among all field operations, soil tillage has the largest share of charge, regardless of the crop grown, followed by straw harvesting and shredding. This is owned by the larger proportions of the rotary harrow (used for tillage) and, consequently, its higher fuel requirements to operate. As for seed production and other agrochemicals (insecticides and herbicides), they have a negligible impact regardless of the agricultural system and impact category considered.

The distribution of burdens follows a similar pattern in both monoculture and rotation scenarios. Nonetheless, a notable difference lies in the carbon credits expressed by the avoided emissions of CO_2. In the context of this study, these credits are attained through the recalcitrant carbon stored in the soil thanks to the return of straw to soil. The results show that the rotation system almost doubles the amount of carbon credits compared to monoculture (1017 kg $CO_2 \cdot ha^{-1}$ in rotation system versus 475 kg $CO_2 \cdot ha^{-1}$ in monoculture). This is consistent with the higher amount of straw returned to soil after chickpea harvesting.

As for PDF and SOC impact categories, their profiles are entirely determined by land-use and land-transformation drivers occurring in the agricultural field (foreground system). In particular, the impact on biodiversity is mostly affected by land-transformation pressures, whereas the impact on soil quality is essentially an effect of land use intensity.

3.4. Environmental performance based on the economic functional unit

In addition to the land management approach, environmental impacts were also analyzed from the economic perspective. For this exercise, a gross margin euro was used as a functional unit, as mentioned in Section 2.3.

3.4.1. Margin gross analysis

Gross margin resulting from the two cropping systems is depicted in Fig. 6 (a detailed report of the economic cost per crop is reported in Tables S1 and S2 of Supplementary material). Both agricultural scenarios show a positive gross margin, corresponding to 5029 €$\cdot ha^{-1}$ and 2585 €$\cdot ha^{-1}$ for rotation and monoculture scenario, respectively. However, a remarkable increase (96 %) is observed when chickpea is introduced in rotation with wheat, thanks to the lower cost for cropping the chickpea and its higher market price compared to wheat (0.9 €$\cdot ha^{-1}$ and 0.29 €$\cdot ha^{-1}$ for chickpea and wheat, respectively).

Across the 3-year time frame, wheat has shown higher cultivation costs (790 €$\cdot ha^{-1}$) than chickpea (679 €$\cdot ha^{-1}$). This is explained by the higher seeds, agrochemicals, and fertilizers demand by durum wheat cultivation with respect to the legume crop. Soil/crop management remains unchanged regardless of the cropping system and growing season (first, second and third in monoculture; second and third in rotation), so that the budgets are the same, accordingly.

By analyzing the individual cost categories, input costs represent the heaviest charge in both systems in each growing year. In terms of net income, chickpea provides to be as the most profitable crop, with a return from selling seeds of 3600 €$\cdot ha^{-1}$, which is dramatically higher compared to the annual profit of durum wheat (from 88 % to 118 %, depending on the growing season and cropping system). In rotation with the legume crop, the income from wheat cultivation increases by 10 % and 16 % (the second and third year, respectively) compared to the monoculture, being the second growing season more profitable than the third (+5 %). This boost is due to the improvement of soil nutrients and chemicals saved from chickpea cultivation, whit benefits for the following crops in terms of productivity and pest and weed control.

3.4.2. Environmental impacts under an economic FU

Even if using one € of gross margin as functional unit (i.e., the environmental impacts are normalized by the margin gross), the rotation system

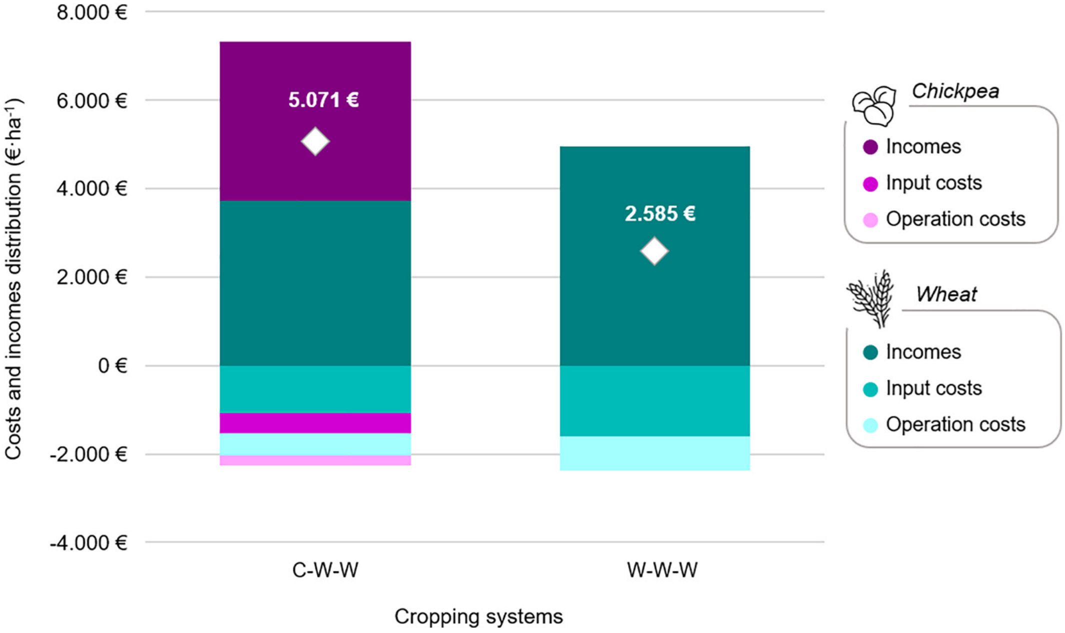

Fig. 6. Gross margin per hectare of the cropping systems under investigation. White diamond indicates the gross margin. C-W-W: rotation system; W-W-W: monoculture system.

proves to be more eco-friendly if compared to the monoculture system (see Fig. 7); with a reduction of environmental loads ranging between 46 % and 69 %, depending on the impact category. This demonstrates that at least in this field of study, although the environmental performance of the cropping systems differs depending on the functional unit considered, there are no trade-off issues between functional units. More in-depth details are given in Table S6 of the Supplementary material.

4. Discussion

Several studies focusing on the environmental performance of wheat grown under rotational regimes have been conducted previously (González-García et al., 2021; Rebolledo-Leiva et al., 2022a, 2022b; Saeed et al., 2022). However, no available reports were found for the environmental improvement after the introduction of chickpea into a wheat-based rotation system. In addition, the assortment of methodological options (functional unit, system boundaries, allocation procedures, etc.) that can be considered when performing an LCA analysis adds additional difficulties to direct comparison of results. However, extensive literature can be found on the improvement of the environmental profile when legumes are introduced in rotational regime (Falcone et al., 2019; Rebolledo-Leiva et al., 2022a; Zingale et al., 2022), in agreement with the data handled here for chickpea.

Consistent with previous studies (Costa et al., 2021; Falcone et al., 2019), N-based fertilization stands as the central factor shaping environmental burdens across all impact categories. This result is the combined effect of on-field emissions during the application of fertilizers and fuel requirements for cropping management. In this regard, Prechsl et al.

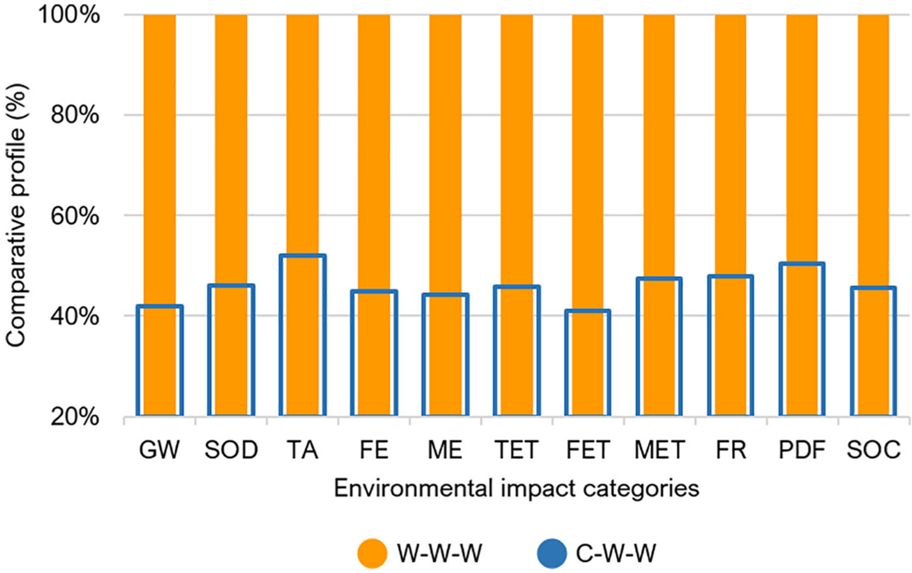

Fig. 7. Comparison of environmental profiles of monoculture and rotation systems per € of gross margin. (C-W-W: rotation system, W-W-W: monoculture system, GW: Global warming, SOD: Ozone depletion, TA: Terrestrial acidification, FE: Freshwater eutrophication, ME: Marine eutrophication, TET: Terrestrial ecotoxicity, FET: Freshwater eutrophication, MET: Marine eutrophication, FR: Fossil resource, PDF: Global potential species loss, SOC: Soil organic carbon deficit).

(2017) reported a contribution of 50 % of total GW impact due to the large amount of fossil fuel needed for fertilizers manufacturing. González-García et al. (2021) also identified that several categories (GW, TA and FR) were considerably affected by the high energy demand of synthetic fertilizers for their production. In addition to fuel combustion, our results show the important weight of the raw material extraction on the ecotoxicity categories (TET, MET, FET) in terms of metal emissions, mainly copper.

Numerous studies agree that the dose of mineral fertilizers commonly applied to crops exceeds the amount that the plant is able to absorb (Cui et al., 2018; Wuepper et al., 2020). This surplus of nitrogen, which on average accounts for two-thirds of the mineral nitrogen applied, ends up in water and air causing significant environmental damage (Global Change Data Lab, 2021). In this regard, it is widely recognized that a wise fertilization can trigger significant environmental benefits without negatively affecting yields (West et al., 2014; Yousaf et al., 2017).

The introduction of legumes is an agronomic strategy that can reduce the amount of fertilizer applied to crops due to their ability to fix nitrogen in symbiosis with *Rhizobium* bacteria (Nemecek et al., 2015). In fact, an adequate dose of fertilizer is highly recommended when growing legumes, as high nitrogen concentrations inhibit their nitrogen-fixing capacity (Yousaf et al., 2017). Another strategy that contributes to reducing fertilization rates is to return straw to soil. This practice has been recognized to improve the retention of nutrients in the soil, as well as to make them more available to plants (Bai et al., 2020). As highlighted by González-García et al. (2021), it is important to couple these options with other eco-friendly management such as precision farming (Heidari et al., 2017) for maximizing the agronomic benefits (e.g., soil fertility enhancement) while limiting the associated drawbacks (e.g., N_2O and NO_3^- emissions).

Intercropping wheat with legumes and returning straw to the field have many other non-designated benefits in addition to providing nutrients. Straw can be used as a mulching layer to improve soil properties, such as its physical structure, water-holding capacity, temperature regulation and microbial life (Chen et al., 2021; Qin et al., 2022). Incorporating legumes, on the other hand, has the potential to increase biodiversity, mobilize phosphorus, reduce weed and pest populations and improve soil structure (Köpke and Nemecek, 2010; Saget et al., 2022). Improving the physical structure of soil allows for less tillage with meaningful benefits, since tillage is the field operation that exhibits the highest contribution to the overall environmental profile (Câmara-Salim et al., 2021; Jeswani et al., 2018; Nemecek et al., 2015).

Regarding plant protection products, emissions derived from their application on the field have a negligible influence on overall environmental profile. This finding is in line with the results of other studies, except those that analyze crops with high agrochemical demand, for example, potato and maize (González-García et al., 2021; Rebolledo-Leiva et al., 2022b).

In terms of biodiversity, land transformation is identified as the main driver of species loss. Likewise, Semenchuk et al. (2022) stated three quarters of species extinction is caused by land conversion. When comparing the damage to biodiversity between the two scenarios, non-significant differences are found. Such results contradict many studies that point out that rotations promote species diversity (Beillouin et al., 2021; Köpke and Nemecek, 2010; Mudgal et al., 2010). In this sense, a refinement of the model underlying PDF assessment is needed, so that the model detects specific crop management practices, such as rotation with legumes. In addition, to conduct a comprehensive assessment on the loss of biodiversity, it is necessary to consider other drivers of biodiversity dynamics besides land use. For example, climate change, pollution, overexploitation, and invasive alien species (Winter et al., 2017). Furthermore, the assessment needs to be extended to the remaining taxa (bacteria, fungi, invertebrates) to fully represent biodiversity. This optimization and refinement of biodiversity metrics will make it possible to assess whether changes in agricultural practices shift environmental impacts to the biodiversity loss, which is ultimately essential to achieve truly sustainable agriculture.

On the other hand, SOC depletion is driven by land occupation, which is consistent with the observations made by Brandão and Canals (2013). Contrarily to PDF, SOC indicator is sensitive to rotation practices and reflects the better soil quality of these type of regimes due to their higher carbon input. In line with these results, Tiemann et al. (2015) reported SOC gains of 8.4 % to 13.9 % in rotations compared to monoculture regimes. As Blanco-Canqui et al. (2022) point out, this increase in soil carbon content is related to the higher biomass production of rotation systems. However, given the influence of returning straw for soil carbon stock (Fang et al., 2019; IPCC, 2019b; Palm et al., 2014), SOC fails to consider the specific amounts of straw returned in its model. In this way, it allows for only absolute choices, either 100 % straw retained, or 100 % straw removed/burned. Following IPCC guidelines (IPCC, 2019b), it was assumed that in the scenarios where straw is returned, that is 100 %, regardless of the specific proportion of straw retained. Although other soil quality indicators are available in the literature (Sala et al., 2019; UNEP-SETAC Life Cycle Initiative, 2019), they do not have sufficient resolution to account for variations in SOC levels linked to this specific agronomic practice. To address this, IPCC guidelines offer the possibility of using direct field measurements with its Tier 3 approach. In any case, it would be very valuable to develop a more accurate model that reflects in more detail the straw retention practices such as crop simulation models.

Considering the economic function of agriculture, the rotation system still shows the best environmental performance, and even improves it considerably, since the incorporation of chickpea results in a substantial increase in gross margin. Rebolledo-Leiva et al. (2022a, 2022b) reported profit growth from 19 % to 51 % for scenarios where lupine preceded wheat. Similarly, Nemecek et al. (2015) presented that rotation systems comprised lower costs and higher yields compared to wheat monoculture. However, even better results could be obtained if farmers adjust the applied agrochemical dosage to the specific requirements of the rotation regime, leading to higher economic benefits and lower environmental burdens. As mentioned earlier, an excessive use of agrochemicals is a common practice among farmers (Global Change Data Lab, 2021). In some cases, this is a consequence of the lack of knowledge about the advantages of rotations in reducing agrochemical use (Wang et al., 2021), especially when a legume is introduced. Therefore, information and education campaigns on best agricultural practices could go a long way in improving performance (Sonja et al., 2011).

5. Conclusions

The introduction of chickpea in the wheat-based agricultural system in the Mediterranean context has resulted in significant improvements from both environmental and economic points of view. However, fertilization practice remains the major issue in the rotation system. Thus, not only the incorporation of legumes but the optimization of fertilizer application is the key to delivering a more sustainable agriculture. Conversely, returning straw to the field has led to a notable reduction of GW burdens. This study aims to provide valuable information that, if implemented, could contribute to achieving several Green Deal targets and SDGs, such as zero hunger (SDG 2), responsible consumption and production (SDG 12), and climate action (SDG 13). Future research could address the development of more comprehensive indicators of biodiversity and soil quality to fully represent them in the analysis of the environmental impact of the agricultural sector. In addition, the environmental consequences of displaced crops (due to the introduction of new intercrops) could also be assessed when promoting rotation systems.

CRediT authorship contribution statement

Sara Lago-Olveira: investigation, methodology, software, writing, visualization. Ricardo Rebolledo-Leiva: writing, editing, and reviewing. Pasquale Garofalo: data collection and reviewing. Maria Teresa Moreira: supervision, reviewing, editing, and writing. Sara González-García: supervision, investigation, funding acquisition, reviewing, and editing.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.165124.

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