



Promoting more sustainable agriculture in the Moroccan drylands by shifting from conventional wheat monoculture to a rotation with chickpea and lentils

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ABSTRACT

Modern agriculture is linked to desertification, massive biodiversity loss and environmental degradation of the ecosystems. In contrast, crop rotation represents an agronomic approach included in conservation agriculture with important environmental and agronomic benefits, such as N fixation, pest and weed control, improvement of soil characteristics and reduction of crop fertilizer demand. Wheat is a staple food in Morocco, as are legumes, which are present in a wide variety of Moroccan recipes and represent an important source of energy and nutrients. The present study evaluates the environmental performance of incorporating chickpea and lentils in a crop rotation system in Morocco that aims to decrease the environmental footprint of the traditional wheat-based crop. An attributional Life Cycle Assessment was conducted in three cropping systems that are grown in two-year cycles: R1 (chickpea:wheat), R2 (lentil:wheat) and M (wheat:wheat). Emissions were quantified in terms of life-cycle related environmental impacts and compared between cropping systems based on two functional unit (kg of wheat harvested). Rotation systems stand out as the most environmentally friendly, with the most notable reductions in the categories of stratospheric ozone depletion and water scarcity (34 % and 50 %, respectively). The environmental improvement from crop rotations was most significant when considering the calculation basis of hectare cultivated versus kg of wheat, which is due to the estimated yield trade-offs in both approaches. In terms of biodiversity loss, no significant differences were observed between crop rotations and monoculture, as the impact on this indicator is mainly attributed to land conversion pressures. This study provides guidance for better formulating crop rotation strategies in the Mediterranean and similar arid regions. Future research should also assess the effects of agriculture on ecosystem services to provide a more comprehensive analysis to support decision making.

1. Introduction

Since the Green Revolution in the 20th century, agriculture has been characterized by intensive use of agrochemicals (e.g., mineral fertilizers and plant protection products), water, and heavy mechanization in an effort to maximize yields (Muhammed et al., 2018). However, it is widely recognized that this agricultural model, beyond improving yields in the short term, compromises future food production by undermining ecosystem balance (Landis, 2017; Tang et al., 2018; Rose et al., 2023).

According to Rossi (2020), 52 % of fertile land is already degraded, with a loss rate of 10 million hectares per year (Hossain et al., 2020). The African continent is particularly vulnerable to these desertification pressures, for which FAO has predicted that two-thirds of its arable land is at risk of being lost by 2050 (Rossi, 2020).

Agriculture is the main source of staple food but to some extent it has caused a great impact on biodiversity (Dudley and Alexander, 2017). According to a recent publication by the World Wildlife Fund (WWF, 2022), wildlife population has declined by 69 % since 1970, mainly due

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to the loss and fragmentation of natural habitats and environmental pollution (Azevedo et al., 2015; Chaudhary and Brooks, 2018; Barbarossa et al., 2021). In this regard, agriculture is known to be the cause of approximately one third of global greenhouse gas emissions and 78 % of eutrophication of oceans and freshwater bodies (Ritchie and Roser, 2022). A decline in biodiversity and soil quality critically affects ecosystem services on which human well-being is based (Landis, 2017; Drobniak et al., 2018; de Graaff et al., 2019). For instance, birds and insects play an important role in pollination, on which 75 % of food crops depend (Potts et al., 2016; Katumo et al., 2022), and soil microorganisms are essential for nutrient cycling and the provision of food, fibers and other raw material (Wall and Nielsen, 2012; Zhang et al., 2021).

Damage to ecosystems and their associated services is not only an environmental, but also an economic and social problem that jeopardizes the achievement of most of the United Nations Sustainable Development Goals (SDGs) (Yin et al., 2021) including food, and water security. With the world population expected to grow to 9.7 billion by 2050, meeting future food demand in a sustainable manner poses an even greater challenge for agriculture. Despite the difficulties, it is essential that the path to food security goes hand in hand with alternative models that maintain or even increase food production while preserving ecosystems (Watson et al., 2021). FAO suggests conservation agriculture as a promising approach to increase yields through sustainable intensification (Corsi and Muminjanov, 2019). Unlike conventional agriculture, this model aims to maintain ecosystems based on three main axes: minimal mechanical soil disturbance, permanent organic soil cover and species diversification (Corsi and Muminjanov, 2019). Institutions such as ICARDA (International Center for Agricultural Research in the Dry Areas) and INRA Morocco (National Institute for Agricultural Research) are working together to increase cereal yields using the conservation agriculture approach in the low rainfall regions of North Africa (ICARDA, 2021). Morocco is leading the transition to conservation agriculture through the Moroccan Collaborative Grant Program (MCGP), a research project developed between INRA and ICARDA with the main objective of establishing conservation agriculture on one million hectares of arable land by 2030 (ICARDA, 2021; INRA, 2021).

Agriculture is at the backbone of the Moroccan economy, accounting for 14 %–20 % of its GDP and 40 % of total employment (El Mekkaoui et al., 2021). Approximately 65 % of arable land is devoted to cereal crops, with wheat being the main commodity on a gross value basis (El Mekkaoui et al., 2021). Although cereals are predominantly grown in monoculture schemes (Bishaw et al., 2021), crop rotations with legumes are being promoted (ICARDA, 2021), particularly with chickpeas, lentils and beans. Indeed, it is recognized that legume-based rotations are clearly more economically advantageous than monocrop regimes in dryland areas of Morocco (Yigezu et al., 2019). Legume crops play a vital role in the country's food security and economic development by being part of many traditional dishes and an important source of protein (Badraoui et al., 2016; Otieno et al., 2020). Its remarkable ability to uptake atmospheric nitrogen into molecules easily uptake by plants contributes to reducing the need for mineral fertilizers (Köpke and Nemecek, 2010) and, by extension, to reducing and stabilizing production costs, as these chemicals are expensive and vulnerable to market fluctuations (Abbott and Borot de Battisti, 2011; IFPRI, 2022). Among other agronomic and environmental benefits, crop rotations contribute significantly to increasing soil organic matter (SOM) (EIP-AGRI, 2016), which in turn, supports soil functions such as water infiltration, water holding capacity, erosion protection, and nutrient storage for plants and soil biota, in which SOM plays a key role (Palm et al., 2014; Hatten and Liles, 2019). In addition, crops considered in rotations can act as break crops (e.g., competing with pests and weeds for resources) and/or nitrate scavengers (e.g., absorbing excess nitrogen) (Blanco-Canqui et al., 2022).

In line with this, the present study evaluates the environmental

performance of combining wheat with two leguminous crops (lentils and chickpeas) in the Mediterranean region of Morocco. For this purpose, the Attributional Life Cycle Assessment (ALCA) methodology has been applied to verify whether these combinations outperform monoculture in environmental terms. The LCA methodology has proven to be a valuable tool not only to determine the environmental profile of cropping systems, but also to identify critical loads throughout their life cycle and within a wide range of environmental problems (so-called impact categories) and, based on this, suggest specific improvement measures (González-García et al., 2021; Rebolledo-Leiva et al., 2022a).

Some previous research has explored the environmental aspects of crop rotation systems through LCA. One of the pioneers was van Zeijts et al., who in 1999 dealt with how to assign fertilization emissions in crop rotations based on crop uptake and efficiency. Several subsequent studies have mostly focused on generating bioenergy and biofuels with lower environmental impact by using crop rotation systems (Styles and Jones, 2007; Monti et al., 2009; Arnold, 2010; Feng et al., 2010; Krohn and Fripp, 2012; Grau et al., 2013; Souza and Seabra, 2013). In 2010, Köpke and Nemecek conducted an in-depth analysis of the ecological benefits of fava beans in rotation and emphasize the need to study these benefits at a whole rotation level rather than as an individual crop to effectively incorporate them in the assessment. Further studies have followed that analyzed the environmental performance of using different legumes (such as lupin, oilseed rape, soybean, chickpea, and pea) in rotation with crops like wheat, maize, barley, and paddy fields (Nemecek et al., 2015; Hokazono and Hayashi, 2015; Cai et al., 2018; Morandini et al., 2020; Costa et al., 2021; Costantini and Bacenetti, 2021; Sun et al., 2021). Some authors sought to refine LCA methodology to reflect cropping systems more accurately, for instance, adjusting the modeling of nitrogen emissions to local conditions (Nitschelm et al., 2018), developing new tools, like the MiLA tool, to estimate GHG emissions (Peter et al., 2017). Additionally, some studies focused on the multifunctionality of agricultural systems and testing how different functional units affects environmental results (Cámara-Salim et al., 2021; Volanti et al., 2021). Research has been also conducted to study how various crop combinations and farming methods perform, including the use of organic models and improved tillage techniques (Zhou et al., 2019; Sun et al., 2022). Panoutsou et al. (2022) even explored the social impacts and benefits of these practices using a participatory approach, which led to multi-stakeholder insights on rotations.

While some research has been conducted on the environmental performance of growing wheat in rotation with legumes, to the best of our knowledge, no such research has been conducted in Morocco. Since the success of crop rotation systems depends on various factors, including the types of crops used, their position in the sequence, and specific pedoclimatic conditions (Nemecek et al., 2015), this study focuses on the environmental performance of two crop-specific rotation designs in Moroccan conditions. Overall, this study aims to contribute to achieving more sustainable agriculture in Morocco, as well as in other similar arid regions, ultimately contributing to several SDGs, including those related to food security (SDG 2), water (SDG 6), climate (SDG 13), oceans (SDG 14) and land (SDG 15).

2. Material and methods

2.1. Goal and scope of the study

The objective of this work is to conduct an environmental assessment of the incorporation of lentils and chickpeas in two rotational systems intended to grow wheat as the main crop and to compare their environmental profiles with that of wheat monoculture. The cropping systems under study are representative of the farming practices that are in place in the Mediterranean region of Morocco (Khémisset province for the Rabat-Salé-Kénitra region; and Settat and Benslimane provinces of the Casablanca Settat region, northwest Morocco), which is

characterized by hot, dry summers and mild, wet winters, with rainfall ranging from 181 to 571 mm per year (period 2005 to 2020). The study area is about 50,000 to 80,000 ha for chickpea, 40,000 to 50,000 ha for lentil and 2.5 to 4 million ha for wheat. The soils found in the region are deep Vertisols with clay texture (50 % clay), with a depth of more than 90 cm. Their upper part (upper 30 cm) has an average soil organic carbon content (1–1.5 %) and pH ranging from 6 to 9.

To carry out the assessment, a system boundary was established from the cradle to the farm gate, as shown in Fig. 1. This scope ranges from the extraction of resources (e.g., minerals, fuel), to the manufacture of inputs (e.g., fertilizers, plant protection products, seeds) and field machinery (e.g., tractor, harvester, etc.), as well as the use of machinery in the operation phase, its maintenance and end-of-life management.

2.2. Life cycle inventory

Once the system boundaries were established, an inventory of resources and emissions was developed. For this purpose, two subsystems can be identified within the system boundaries: the foreground and background systems. The foreground system consists of primary data from agricultural activities involved in crop growth, while the background system is composed of processes that support the foreground system but cannot be directly manipulated (i.e., extraction and production of all external inputs and tailpipe emissions and tire wear). Primary data were collected through targeted interaction with farmers and supplemented by an agronomic report from the Moroccan Ministry of Agriculture and Rural Development (2000) on the technical characteristics (e.g., diesel consumption, weight, effective working capacity) of agricultural machinery, and ICARDA field studies on the agrochemical inputs (e.g., fertilizers and plant protection products) applied in Morocco (Devkota et al., 2022), which form the basis for modeling the crop rotation scenarios analyzed. The data composing the background system were acquired from the Ecoinvent v3.9 database (Wernet et al., 2016). The share of machines used in each agricultural activity was estimated using the specific weight, lifespan and operation time of each machine.

2.3. Description of the cropping systems under study

The cropping systems are arranged in two-year cycles (corresponding to the years 2020–2022), with each cropping period (one year) starting once the previous crop is harvested and ending with the harvest of the current crop. The two rotations evaluated are R1, consisting of chickpea (*Cicer arietinum* L.) and wheat (*Triticum aestivum* L.), and R2, comprising lentils (*Lens culinaris* Medik.) and wheat (Fig. 2). Chickpea and lentils are grown before wheat, so wheat can benefit from the biological supply of nitrogen from these legumes.

The various agricultural operations that occur during each growing

season are organized into three main stages: field preparation, crop growth, and harvesting (Fig. 1). Field preparation includes all activities focused on soil preparation prior to planting. As all the cropping systems studied are under conventional management, the tillage performed to prepare the seedbed is intensive. Crop growth corresponds to the sowing of seeds and the application of agrochemicals (i.e., fertilizers and plant protection products) and other inputs, such as water. Finally, harvesting involves the process of harvesting, threshing and baling.

2.3.1. Growing leguminous crops

Chickpea and lentils were grown following the same agricultural activities; therefore, the same growth protocol applies to both crops. Legume cultivation activities start at the end of July, immediately after wheat harvest, by performing primary tillage using a deep disk. Around November–December, two more tillage activities are performed: a semi-deep tillage and a soil leveling tillage, which are carried out using a disc harrow and a roll crosskill, respectively. During the same period, NPK 15-15-15 fertilizer (200 kg ha⁻¹) is applied using a fertilizer spreader, after which legume seeds are sown (80 and 60 kg ha⁻¹ of chickpea and lentil seeds, respectively).

In the legume growth phase, weeds are manually removed two or three times, usually four weeks after the beginning of growth. In addition, manual control is supplemented by a chemical treatment consisting of 1.5 l ha⁻¹ of Stomp® (45.5 % of pendimethalin) after sowing and a second chemical treatment consisting of 0.75 l ha⁻¹ of Fusilade Max® (12.5 % of fluazifop-p-butyl) when weeds emerge. Both chickpea and lentils are grown under rainfed conditions and, therefore, receive no water input. In May, once the legumes have grown, they are harvested and threshed with a combine harvester. In the case of chickpea, 700 kg ha⁻¹ of grains and 3020 kg ha⁻¹ of straw are harvested. As for lentil, it yields the same amount of grain, while slightly higher amount of straw (3400 kg ha⁻¹). Regardless of the legume crop, all straw (100 %) is packed with a pick-up baler and sold or used as animal fodder. Table S1 of the Supplementary Material compiles all the information related to the cultivation of chickpea and lentil.

2.3.2. Cultivation of wheat

The wheat growing season starts at the end of July by applying primary tillage with a deep disk. Several months later, between October and December, three more tillage operations are carried out by means of a vibrotiller and a roller; and immediately after, 165 kg of wheat seeds are sown in combination with one third of the total fertilizer supplied, for which a seeder drill is used. The remaining two-thirds of fertilizer inputs are applied one month later (January) using a fertilizer spreader. In total, 300 kg ha⁻¹ of NPK 15-15-15 and 50 kg ha⁻¹ of ammonium nitrate (AN 33 %) are supplied to wheat. Unlike the legume crop, weeds are only controlled by a chemical treatment, consisting of the application of Mustang® 360 SE herbicide (0.6 l ha⁻¹) over the entire field

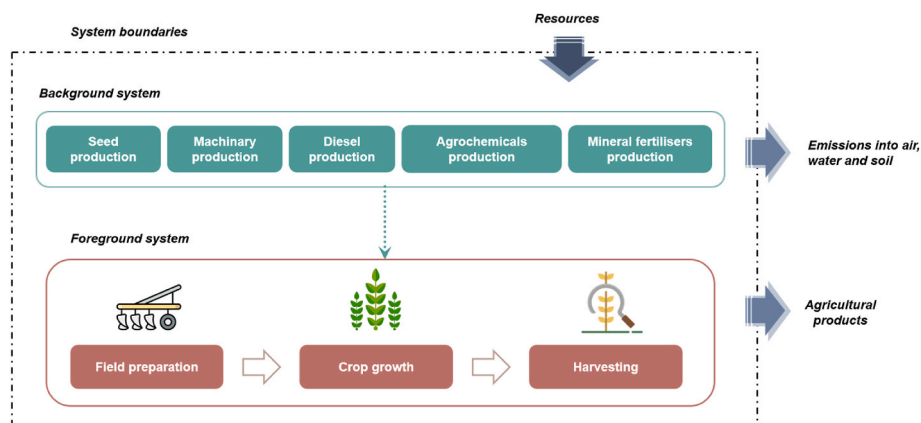


Fig. 1. System boundaries of cropping systems.

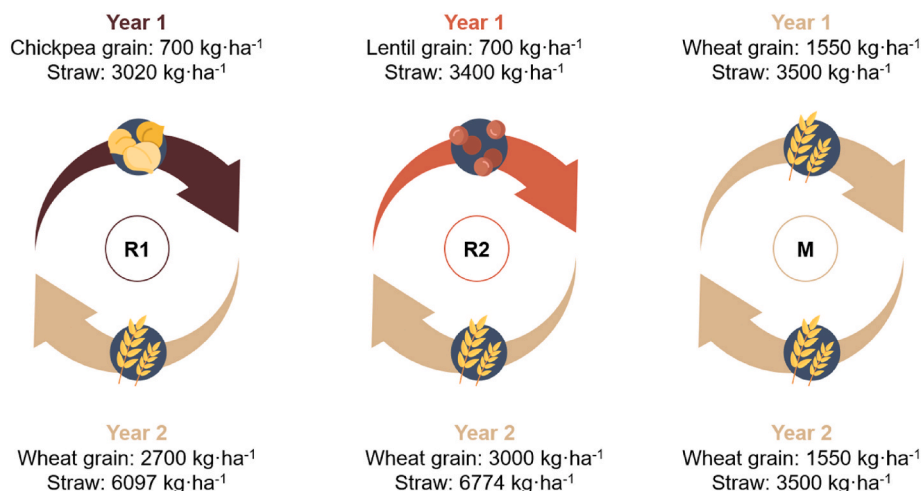


Fig. 2. Layout of the cropping systems under study.

between January and March. This herbicide contains 6.25 g l⁻¹ of florasulam and 300 g l⁻¹ of 2,4 D ester as active ingredients. Despite the numerous scientific evidence supporting the ability of legumes to capture atmospheric nitrogen and make it available to subsequent crops (Foyer et al., 2019; Köpke and Nemecek, 2010), as well as their capacity to suppress weeds (Kocira et al., 2020), no differences in agrochemical dosage are applied to wheat depending on the cropping system considered (monoculture or rotation).

In Morocco, wheat is predominantly grown under rainfed conditions (83 %), although a small percentage of the cultivated area (17 %) is irrigated (ICARDA, 2021). In this area, 2500 m³ ha⁻¹ of water are applied by both surface furrows and sprinkler irrigation before plating (when soil conditions are too dry) and during the growth phase, especially during flowering, and until the wheat matures. A total of 1101 kWh·ha⁻¹ is consumed for this operation. In May–June, wheat is harvested and threshed with a combine, after which part of the straw is baled with a baler. Wheat yields vary substantially depending on the regime in which it is grown. In rotation systems, wheat yields represent 2700 and 3000 kg ha⁻¹ of grain (R1 and R2, respectively) and 6097 and 6774 kg ha⁻¹ of straw (R1 and R2, respectively). As for the monoculture regime, 1550 kg of grain and 3500 kg of straw per hectare are harvested. Wheat straw has several purposes, being the main fodder for herds (83 %) and the rest burned (0.5 %) or returned to the field (16 %). Table S2 of the Supplementary Material provides full details of the wheat cultivated.

2.4. Field emissions

Emissions from the application of fertilizers and plant protection products were estimated according to several models. Direct N₂O emissions originating from straw decomposition and mineral fertilizer application were quantified considering an emission factor of 0.01 (N released as N₂O), as determined by IPCC (2019a). Indirect N₂O emissions can be leached or volatilized and eventually deposited in the soil. According to IPCC (2019a), emission factors of 0.240 and 0.011 were used for the fraction of N that is leached and the amount of N–N₂O lost in the process, respectively. Moreover, N₂O deposition was quantified using 0.11 and 0.05 as the fractions of N volatilized for NPK and AN fertilizer (respectively), as well as 0.01 as the emission factor for N₂O emissions from soil N deposition (Intergovernmental Panel on Climate Change (IPCC), 2019a). NH₃ emissions were estimated following EMEP/EEA (2019) guidelines and assuming a temperate climate and high pH. Emission factors of 0.094 and 0.033 kgNH₃·kgN⁻¹ applied were used for the complex fertilizer (NPK) and AN, respectively. NO₂ emissions were calculated using the emission factor of 0.04 kgNO₂·kgN⁻¹

applied for both fertilizers. Regarding the emissions of NO₃⁻ to water, they were quantified based on the regression model developed by Faist et al. (2009). The model includes in its calculation the annual rainfall, the mineral supplementation of nitrogen (except for those fractions already lost through NH₃, NO₂ and N₂O emissions), the nitrogen content of organic matter, the nitrogen uptake by the crops, the clay content in the soil (50 %) and the depth of the crop roots (1.2 m for wheat, 1.05 m for chickpea and 0.63 m for lentil). The phosphate emitted by the complex fertilizer was estimated implementing the SALCA-P model (Prasuhn, 2006). The emission factors of 0.07 kg P·ha⁻¹·yr⁻¹ and 0.175 kg P·ha⁻¹·yr⁻¹ were assumed for the leaching and run-off emission pathways, respectively. For emissions of other agrochemicals (herbicides, insecticides), it was considered, according to PEFCE guidance (European Commission, 2018), that 1 %, 9 % and 90 % of the active ingredient ends up in water, air and soil, respectively. A compilation of all emission factors can be found in Table S3 of the Supplementary Material.

Another important source of agricultural emissions is land-use change (LUC) (Schmidt et al., 2015), which refer to those emissions resulting from altered land use patterns. Depending on whether they occur in the agricultural field or elsewhere, they are denoted as direct (dLUC) and indirect land-use change (iLUC) emissions, respectively. The dLUC emissions were estimated as 34.37 kg CO₂eq·ha⁻¹·yr⁻¹ applying the biophysical model developed by Schmidt et al. (2015). Regarding dLUC emissions, they were quantified assuming a carbon content on a dry weight basis of 49 % for wheat (Intergovernmental Panel on Climate Change (IPCC), 2019a), 42 % for chickpea (Nazari et al., 2019) and 44 % for lentils (Gan et al., 2009). In addition, 16 % of straw was considered to be converted to recalcitrant soil organic carbon (SOC) (Fang et al., 2019). Since straw returned to the field increases soil carbon content over long periods of time contributing to mitigate climate change (Fang et al., 2019; González-García et al., 2021), dLUC was regarded as an environmental credit.

2.5. Functional unit and allocation

As argued by several authors, agricultural systems offer multiple functions, so the selection of the functional unit (FU) should not be limited to only one (Nemecek et al., 2015; Rebolledo-Leiva et al., 2022a). In the present study, two FU were chosen to quantify and compare the environmental impacts associated with the agricultural systems studied: a land management FU (1 ha·year) and a productive FU (one kg of harvest wheat). The former reflects the intrinsic value of land for providing multiple ecosystem services linked to agriculture. This FU helps to understand how to better manage land to reduce environmental

impact and preserve its quality for future agricultural production. Regarding the latter, it reflects the purpose of farming systems to produce wheat as the main product. In this case, FU contributes to reducing the impact per unit of production. As the assessment was carried out considering each farming system as a whole, it was not necessary to allocate environmental burdens between products and co-products.

2.6. Life cycle impact assessment

To transform the inventory data (inputs and outputs) into environmental impacts, 12 impact categories were used due to their relevance to the agricultural sector (Nemecek et al., 2011; UNEP-SETAC Life Cycle Initiative, 2019; Costa et al., 2020). The following midpoint impact categories were quantified using ReCiPe 2016 V1.06 Hierarchist Midpoint method World (2010) (Huijbregts et al., 2017): 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, Water Scarcity (WS) was assessed applying AWARE (Available Water REmaining) method 1.04 and Soil Organic Carbon (SOC) Deficit following the model developed by Milà i Canals et al. (2007) and revised by Brandão and Canals (2013). From an endpoint perspective, global Potential Species Loss (PDF) was quantified applying the field-species relationship (SAR) model (Chaudhary et al., 2015; Chaudhary and Brooks, 2018). The SOC and PDF indicators measure the impact that land use and land transformation drivers have on biodiversity and soil quality. Impacts in these two areas are rarely assessed in agricultural LCA studies due to lack of consensus on the most appropriate model and a comprehensive impact pathway (Vidal-Legaz et al., 2016; Costa et al., 2020). However, they have been considered in the present study by using the indicators recommended by UNEP-SETAC Life Cycle Initiative (2019) (SOC and PDF), on the basis of the relevant contribution that agricultural activities have on biodiversity loss and damage to soil quality. A more detailed description of the PDF indicator is provided in the Supplementary Material. SimaPro v9.3 software (PRé Sustainability, 2022) and Microsoft Excel® 365 MSO were used to quantify the environmental impacts.

3. Results and discussion

3.1. Environmental impacts: land management function

Fig. 3 shows a relative comparative analysis of the cropping systems' performance across selected impact categories, using 1 ha-year as the functional unit. For more details on the absolute values, see Table S4 in the Supplementary Material. Rotation systems (R1 and R2) show the best environmental performance in all impact categories, sharing very similar scores among them. However, their improved performance is limited in terms of ME and PDF, for which R1 and R2 report impact reductions (vs. M) of 4%–5% and 2% for ME and PDF, respectively. These results are largely explained by the higher input consumption of the monoculture (M) regime. While M requires a total fertilizer dose consisting of 666 kg NPK·ha⁻¹ and 100 kg AN·ha⁻¹, the crop rotation systems use 533 kg ha⁻¹ of NPK and 50 kg AN·ha⁻¹ each. In the irrigated area (e.g., 17% of the total cropland), M also consumes twice as much water and energy as R1 and R2 (5000 m³ water·ha⁻¹ and 2203 kWh·ha⁻¹ in monoculture, 2500 m³ ha⁻¹ and 1101 kWh·ha⁻¹ in rotations). In addition, the monoculture undergoes an additional tillage operation, which also contributes to its lower environmental performance, albeit to a lesser extent. As for the similarity of the environmental profiles of R1 and R2, it is consistent with the fact that they are grown using the same operations and inputs, with the exception of seeds, whose difference in type and quantity offered is related to marginal variations in environmental impact (up to 3%).

The biodiversity loss indicator (PDF) is a function of several spatially

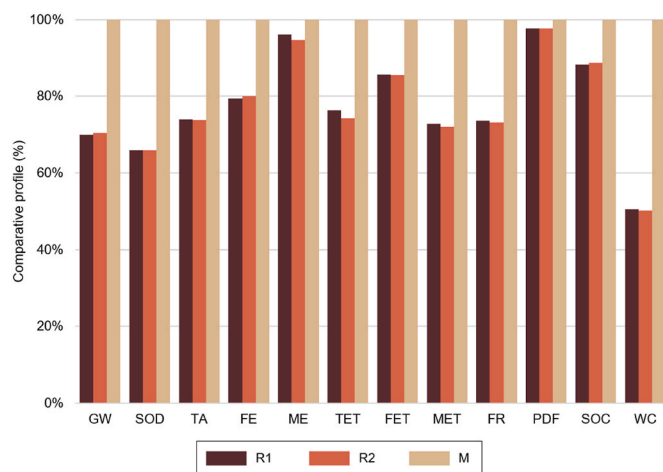


Fig. 3. Relative comparison between the environmental performance of cropping systems per hectare-year. R1 is chickpea:wheat rotation, R2 is lentil:wheat rotation and M is wheat monoculture. Impact categories: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET) and Fossil Resources (FR), global Potential Species Loss (PDF), Soil Organic Carbon (SOC) and Water Scarcity (WS).

dependent factors, such as species richness, the number of endemics and their level of threat, as well as the proportion of natural habitat conserved (Chaudhary and Brooks, 2018). Since the three cropping systems studied are grown in the same ecological region (i.e., Mediterranean coniferous and mixed forests, code: PA0513) (Olson et al., 2001), they share almost the same PDF impact per hectare. The minor difference (2%) is attributed to the type of land use (e.g., intensity level) considered for crop rotation (light cropping) and monoculture (intensive cropping) systems. On the other hand, SOC depends on the extent of area occupied by cropping systems, duration, type of management practices performed (e.g., straw and fertilizer management, cropping intensity, irrigation systems, tillage, etc.), regeneration time of the occupied land and soil properties (IPCC, 2019b). The introduction of a legume in the cropping system plays a decisive role in favor of R1 and R2, as rotation systems result in higher soil carbon gains than monoculture.

3.2. Environmental impacts: productive function

As a whole (i.e., considering the two-year cycle), the monoculture regime has the highest wheat production. However, crop rotation systems lead to a significant increase in wheat yield per year compared to monoculture (74% and 94%, for R1 and R2 respectively), which is consistent with previous studies on wheat and legume rotations (Kirkegaard et al., 2008; Gan et al., 2015; Plaza-Bonilla et al., 2017; Rebollo-Leiva et al., 2022a). When comparing the cropping systems in terms of the production function (kg wheat) (Fig. 4), there are notable changes in the results with respect to those identified per hectare. On this occasion, R2 presents the best environmental performance, ahead of R1. PDF and ME are the only exceptions, for which R2 and M stand out with similar results (see Table S5 in the Supplementary Material for absolute results). In contrast, M has the worst profile in 8 of the 12 impact categories despite producing the highest wheat yield (3100 kg ha⁻¹ compared to 3000 kg ha⁻¹ and 2700 kg ha⁻¹, R2 and R1 respectively). The results of these 8 impact categories suggest that the impacts of monoculture are considerably greater than those of the rotation systems, as their higher wheat yields do not compensate for them.

R1 has a similar environmental impact to M in FE, FET and SOC, while it is ranked as the worst-case scenario (ahead of M) when ME and PDF are considered. The low performance of R1 is largely attributed to

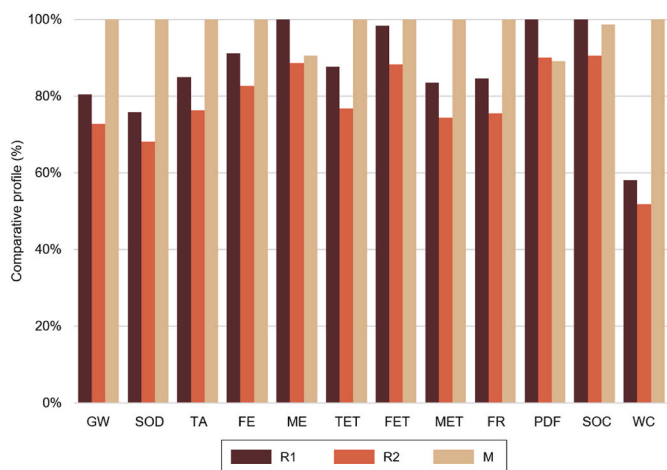


Fig. 4. Relative comparison between the environmental performance of cropping systems per kg of wheat harvested. R1 is chickpea:wheat rotation, R2 is lentil:wheat rotation and M is wheat monoculture. Impact categories: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET) and Fossil Resources (FR), global Potential Species Loss (PDF), Soil Organic Carbon (SOC) and Water Scarcity (WS).

the lower wheat yield compared to monoculture. In the specific case of ME and PDF, this low yield is compounded by the fact that almost the same environmental loads per hectare are obtained, as mentioned above. Therefore, when considering the productive functional unit, the impact of ME and PDF is indirectly proportional to the amount of wheat produced by each system. On the contrary, R2 stands out with the best performance since it has almost the same yield as the monoculture system and its impact per hectare is as low as that of R1. These results reveal that the productive functional unit penalizes cropping systems with lower yields, even when these systems consume fewer resources

and are less mechanized, as is the case with R1. On the contrary, these low-yielding systems are favored by the functional unit of 1 ha, in line with González-García et al.'s results (2021). Considering that the selection of the functional unit affects the results, the adoption of several FU can be a useful approach in the case of agricultural systems (involving multiple functions) to identify trade-offs between FU and to perform a more complete interpretation of the results, as previously noted by other researchers (Yang et al., 2014; Nemecek et al., 2015; Tricase et al., 2018; Costa et al., 2020).

3.3. Analysis of the main factors contributing to the environmental impact

The relative contribution of different factors to the environmental profile of the cropping systems is depicted in Fig. 5. As can be seen, the key factors differ according to the impact category considered.

3.3.1. On-field emissions

On-field emissions are the largest contributor in terms of SOD, ME, TA, FE and GW, regardless of the cropping system evaluated. Their influence is particularly notable in SOD and ME, for which on-field emissions, derived mainly from the application of N-based fertilizers, account for 91 %–97 % of the total load. Specifically, NO₂ emissions to the atmosphere are the most relevant in terms of SOD, while NO₃ emissions to water are by far the main driver of ME. Direct NO₂ emissions from mineral fertilization also have a remarkable effect on GW. Nevertheless, CO₂ emissions related to fuel combustion during field operations and fertilizer manufacturing are also partly responsible for impacts in this category. With respect to TA and FE, NH₃ and phosphate emissions (respectively) from mineral fertilization are of particular concern.

In addition to fertilization, emissions related to the use of plant protection products, straw return in the field and iLUC are also included in the field emissions factor. As for the contribution of crop protection products, this is not appreciable in any impact category, except for FET, where it has a limited influence (12 %) in the form of pendimethalin, the active component of the herbicide Stomp®. The same applies to iLUC,

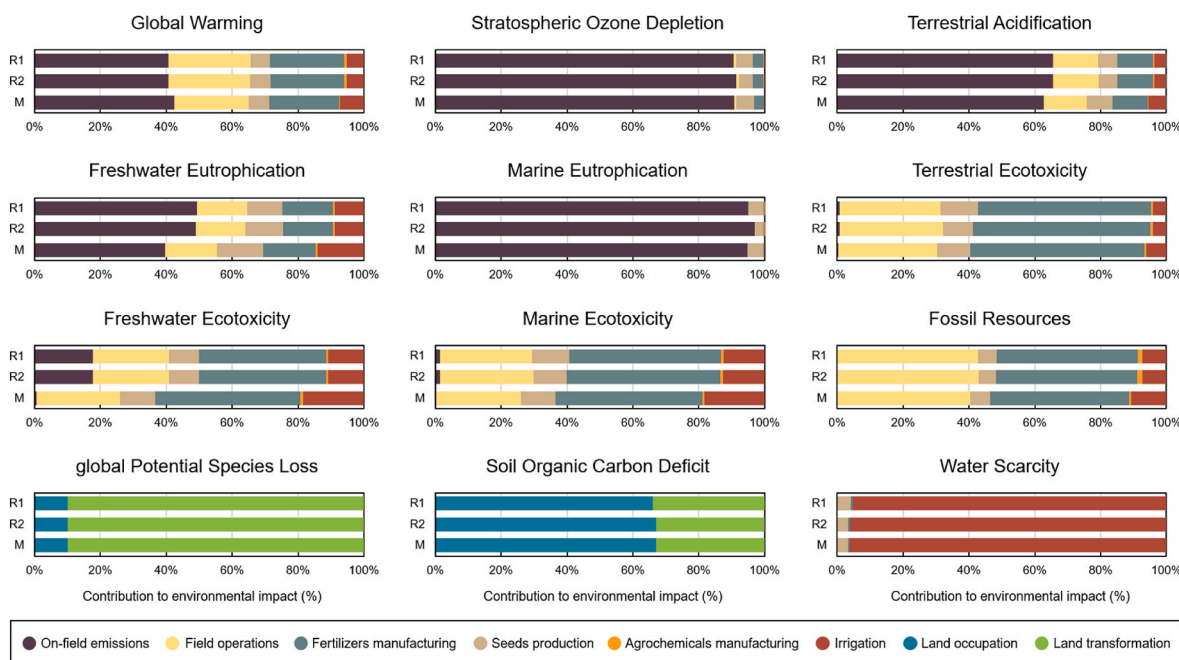


Fig. 5. Contribution of factors to environmental profiles by cropping system. R1 is chickpea:wheat rotation, R2 is lentil:wheat rotation and M is wheat monoculture. Impact categories: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET) and Fossil Resources (FR), global Potential Species Loss (PDF), Soil Organic Carbon (SOC) and Water Scarcity (WS).

which has a minor effect on the environmental profile (less than 5 % of the GW profile). In contrast, the practice of returning straw to the field is associated with noticeable effects on the environmental profile. On the one hand, straw decomposition releases N_2O to the atmosphere, contributing to SOD and GW loads. On the other hand, this practice increases the carbon content stored in the soil (called carbon credits) due to the addition of carbon-rich biomass. In this study, 16 % of wheat straw is returned to the field, resulting in GW reductions of - 33.58, - 37.39 and - 40.16 $kg\ CO_2eq\cdot ha^{-1}$ for R1, R2 and M, respectively. Previous studies have also reported offsetting GW loads in cropping systems by leaving excess straw in the field (González-García et al., 2021; Mattila et al., 2022; Rebolledo-Leiva et al., 2022a). Compared to these previous studies (1.2–11.2 $t\ CO_2eq\cdot ha^{-1}$), the carbon credits reported here are substantially lower, which can be justified by the low yields of the cropping systems studied. However, these modest gains still contribute to lowering the GW impacts.

3.3.2. Fertilizers production and field operations

Fertilizer production plays a key role in toxicity-related categories (TET, FET, MET) through Cu and Zn emissions to water and air. In addition, this factor has a considerable impact on FR due to fuel consumption, which together with field operations, represents approximately 85 % of the total load (both sharing a similar contribution). Among the wide range of field operations carried out in cropping systems, soil conditioning has the greatest impact on the environmental profile. This is mainly due to the relatively high frequency of this type of operations (one primary tillage and 2 to 3 successive tillage operations for seedbed preparation) and the large amount of diesel fuel consumed (Tables S1 and S2 of the Supplementary Material). In this regard, Câmara-Salim et al. (2021), who also identified tillage operations as critical, suggests using more efficient machines and, most importantly, reducing the frequency of tillage. In addition, it is worth mentioning, despite its limited contribution (23 %–31 %), the effect of field operations on toxicity-related categories through emissions from agricultural machinery production in the background system (mostly copper, nickel and zinc).

3.3.3. Irrigation

Concerning the water scarcity (WS) category, irrigation is clearly the process that contribute the most (95 %) due to the large amount of water used for this purpose. Although the irrigated area for wheat cultivation is a minority (17 % of cropland), it is imperative to explore ways to reduce water consumption given the context of the extreme drought in which Morocco is immersed (Ayham, 2022), which is expected to intensify as a result of climate change (Masia et al., 2021). For instance, El Gataa et al. (2022) supported that the use of local drought-tolerant wheat varieties contributes to this purpose. In addition, reuse of urban wastewater can be a favorable alternative to groundwater, although there are some situations, as highlighted by Maesele and Roux (2021), where groundwater use is preferable, such as water-abundant regions or if aquatic plants have advanced tertiary treatments, where the environmental benefits are offset by their high energy consumption. Maintaining optimal soil health is essential to ensure good water infiltration rates and water storage for plant uptake (Anderson, 2021). In this sense, conservation tillage is a recommended practice as it improves these soil functions (water infiltration and storage), in addition to favoring root expansion and protecting soils from high temperatures (Li et al., 2020).

3.3.4. Driver of land-occupation and land-transformation

SOC and PDF are also impact categories determined mainly by a single factor, with land occupation being the main driver of soil quality deterioration (SOC) and land transformation of biodiversity loss (PDF). Similarly, Brandão and Canals (2013) also reported the predominant pressure of land occupation on soil quality over land transformation. On this basis, agricultural practices that improve soil carbon content have a positive impact on the soil quality indicator, such as crop rotations,

reduced or no-tillage, straw deposition and low fertilization (IPCC, 2019b; Anderson, 2021; Mattila et al., 2022). The present study shows a significant reduction in SOC impact when a crop rotation regime (R1 and R2) is applied. However, it is important to note that the model used to calculate SOC has a binary choice for the parameter accounting for how straw is used (either 100 % returned to the soil or 100 % removed from the soil) (IPCC, 2019b), without any possible scenario in between, as it is the case of the scenarios analyzed, where only part of the straw is returned to the field. Therefore, the advantage of rotations over monoculture could be softened if the model was able to capture that monoculture regime return more straw to the field than rotations.

The results for PDF are aligned with those of Semenchuk et al. (2022), who found that land transformation accounts for 75 % of biodiversity loss, although the authors noted that land occupation could be of greater concern (e.g., increasing biodiversity loss by a factor of 4) if all land currently managed at low-medium intensity were used more intensively. Thus, encouraging both aspects (land transformation and occupation) to be considered when defining strategies for more sustainable agriculture. Chiatante and Meriggi (2016) highlighted that maintaining agricultural systems diverse and complex is key to conserving species richness, for which crop rotations have proven to be a favorable practice (Mudgal et al., 2010; Beillouin et al., 2021), providing more diverse habitats and a greater variety of resources (Bavec and Bavec, 2015). In particular, legumes stimulate soil microbial biodiversity through the symbiotic association of their roots with *Rhizobium* bacteria (Lai et al., 2022). Contrary to this scientific evidence, no significant differences between rotation and monoculture systems with respect to PDF are identified in the present study. Furthermore, the PDF indicator estimates biodiversity loss only in terms of land use pressures (e.g., land occupation and transformation), excluding other relevant drivers of the agricultural field, such as air and water pollution (e.g., eutrophication and acidification), climate change, and invasive species (Winter et al., 2017), which should be included in the evaluation in order to be more comprehensive.

3.3.5. Seed and plant protection product manufacturing

Regarding the impact of seed and plant protection product production, it is negligible in all impact categories, with a contribution ranging from 0 % to 15 %, which is in line with previous studies (González-García et al., 2021; Almeida-García et al., 2022; Rebolledo-Leiva et al., 2022a).

3.4. Comparison with Ecoinvent scenarios

Next, the environmental profiles of the scenarios analyzed in this study (R1, R2, M) are compared with the profiles of three new scenarios modeled using the Ecoinvent database. Specifically, one scenario was modeled for each regime, the so-called Ecoinvent scenarios: Ecoinvent R1, consisting of chickpeas and wheat, Ecoinvent R2, consisting of lentils and wheat, and Ecoinvent M, consisting of two years of wheat. They were modeled using the Ecoinvent processes with the geographical scope *Rest-of-World*. For more details on the Ecoinvent processes, see the Supplementary Material. To calculate the environmental impacts of the Ecoinvent scenarios, the same method was used as in the present study, as well as the same functional units to refer to the impacts. As for the impact categories, two were excluded from the comparison (SOC and PDF) due to data limitations to quantify them. This comparison enables the evaluation of whether using an alternative dataset with the same methodological parameters produces different results.

The comparison between the environmental profiles modeled using Ecoinvent and scenarios R1, R2 and M is shown in Fig. 6 for all impact categories and is based on the two FU ($ha\cdot year$ and kg of wheat). A similar environmental performance is observed between Ecoinvent scenarios and R1, R2 and M when the land management function is used, with monoculture being the most unfavorable system. On the other hand, environmental performance differs substantially when the

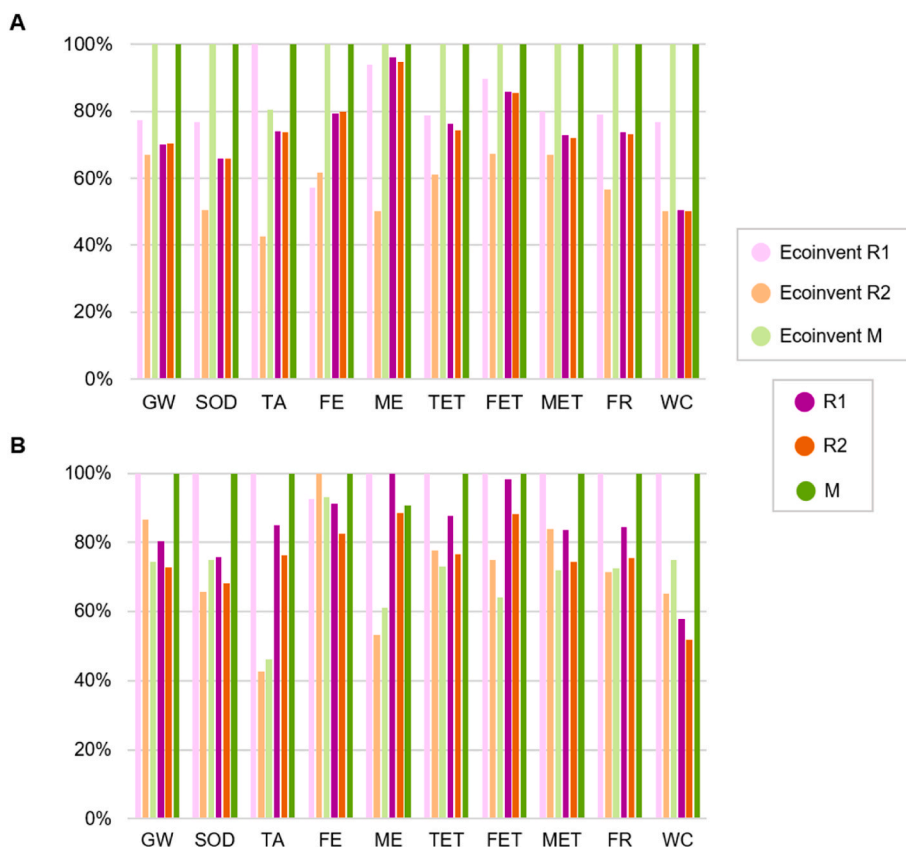


Fig. 6. Relative environmental comparison of R1, R2 and M and Ecoinvent scenarios based on the functional unit hectare-year (A) and kg of wheat harvested (B). Impact categories: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET) and Fossil Resources (FR), global Potential Species Loss (PDF), Soil Organic Carbon (SOC) and Water Scarcity (WS).

production function is considered. On this occasion, the monoculture regime outperforms the rotation systems in the Ecoinvent scenarios while it has the most detrimental profile among R1, R2 and M scenarios. This is explained by the lower wheat production of the rotation systems in the Ecoinvent scenarios, for which an average yield increase of 15 % was considered based on scientific literature (Christen, 2001; Kirkegaard et al., 2008; Gan et al., 2015; Plaza-Bonilla et al., 2017; Rebolledo-Leiva et al., 2022a), compared to increases of 74 % and 94 % recorded by the R1 and R2, respectively. These results support the better performance of the rotations with chickpea and lentil on a land managed basis compared to wheat monoculture, in addition to emphasizing the effect that FU has on the environmental results, favoring specific agricultural systems depending on the FU considered, as it is the case of the rotation with lentils (with high yield) in a productive FU. Tables S6 and S7 of the Supplementary Material provides the absolute results for all Ecoinvent scenarios based on FU1 and FU2, respectively.

4. Further discussion

Mineral fertilization, especially N-based fertilization, is recurrently identified as the main hotspot in agricultural LCA studies. In line with our results, Rebolledo-Leiva et al. (2022a) identified that nitrogen fertilizer application and manufacture determined the environmental profile of wheat-lupine crop rotations. Achten and Van Acker (2016) reach similar results after conducting a meta-analysis of 20 life-cycle inventories of wheat production across Europe. González-García et al. (2021) analyzed several rotation systems aimed at producing wheat and highlighted that not only nitrogen-based emissions, but also the high energy demand of the background processes for fertilizer production, greatly affected most impact categories (GW, SOD, TA, FR, FE, ME).

The use of organic fertilizers such as manure or compost has a high potential to reduce the loads derived from fertilization. In this sense, Rebolledo-Leiva et al. (2022b) indicated reductions of up to 93 % in the environmental profile of wheat-based rotation systems grown under organic conditions compared to the conventional regime. Exceptionally, the authors reported higher loads in organic systems for TA attributed to significant NH_3 emissions from animal manure. Similarly, Pelletier et al. (2008) showed a reduction in global warming gases, ozone depletion and acidification when fertilizing wheat crops with sweet clover green manure.

Legumes are recognized as an environmentally friendly source of N (Wang and Dalal, 2015), which is confirmed by the results of this study showing that the introduction of legumes reduces the impact, between 7 % in FET to 48 % in WS compared to monoculture. Similarly, Almeida-García et al. (2022) reported a significant reduction in environmental loads (up to 119 %) for wheat grown in rotation with lupin (vs. monoculture), along with substantial improvements in grain yields, quality (i. e., specific weight, thousand seed weight), and weed suppression. Moreover, Nemecek et al. (2015) demonstrated in a set of 64 crop rotations the advantageous performance of legumes and highlighted the importance of the position of the legume crop in the rotation to achieve the best environmental and agronomic results. In the present study, legumes preceded wheat in both rotation systems, so wheat was able to benefit from the N-fixing capacity, whose nutritional contribution, as indicated by Nemecek et al. (2015), is higher just after the legume. However, the potential of these crops is not being fully exploited, as farmers apply the same dose of fertilizers and agrochemicals for wheat cultivation, regardless of the agricultural regime considered (monoculture or in rotation with legumes) (Table S2). Even more worrying is the fact that a high fertilizer dose can inhibit the N-fixing capacity of

legumes (Zhao et al., 2022), hindering one of the main motivations for introducing legumes in the first place. Overfertilization is a widespread practice linked to monoculture to maintain yields (Bavec and Bavec, 2015; Global Change Data Lab, 2021). On average, 50 %–60 % of the nitrogen supplied by farmers leaches into the environment (Global Change Data Lab, 2021), causing important pollution issues worldwide (UNEP, 2019). By addressing overfertilization, it could not only improve legume yields, but significantly reduce environmental loads (up to 35 % worldwide) without jeopardizing crop yields (Wang and Dalal, 2015; Global Change Data Lab, 2021).

4.1. Study limitations and future perspectives

The Soil Organic Carbon (SOC) indicator relies on the IPCC guidelines to estimate variations of SOC in soil based on parameters including tillage type, fertilization intensity, and land use (IPCC, 2019b). While valuable when direct measurements are not feasible, the indicator presents limited options for certain parameters, such as the amount of straw returned to fields, making it challenging to accurately represent the analyzed cropping systems. This indicator is regarded as a valuable proxy for assessing soil quality owing to the significant correlation between SOC levels and soil physicochemical and biological properties (Brandão and Canals, 2013; UNEP-SETAC Life Cycle Initiative, 2019). Nonetheless, some authors argue that it is crucial to include other factors impacting soil quality, such as erosion and compaction, which are relevant in the agricultural sector and do not relate to SOC levels (Joensuu and Saarinen, 2017).

The biodiversity loss indicator neglects the beneficial effect of integrating legumes on biodiversity richness, above and below ground, as evident from Mudgal et al. (2010), Bavec and Bavec (2015) and Beilouin et al. (2021). This indicator concentrates solely on mammals, amphibians, birds, plants, and reptiles and fails to consider other taxonomic groups of equal importance, such as insects, bacteria, fungi, and nematodes. Furthermore, while the indicator is responsive to different land-use intensities, its characterization factors are not detailed enough to consider particular practices such as crop rotations. Furthermore, there is a lack of indicators to assess biodiversity loss due to other pertinent drivers, such as the use of toxic active ingredients during chemical pest control and the impact of climate change (Winter et al., 2017; Lago-Oliveira et al., 2023). While this is a highly valuable start in measuring the impact of agriculture on biodiversity, further efforts should be made to develop more comprehensive indicators that cover more drivers and taxa and are more detailed in terms of land management practices.

Moreover, agricultural systems are able to provide numerous ecosystem services beyond food production, including carbon sequestration, nutrient cycling, water supply, and pest control, among others (Palm et al., 2014). However, the present study solely assesses the environmental burdens without considering their impact on the ecosystem services, nor does it estimate the ecosystem services provided by the cropping systems. Further development is necessary to quantitatively measure the impact on ecosystem services and incorporate it into the overall environmental profile. This will enhance the comprehension of the environmental sustainability of agricultural activities, and ultimately improve decision-making processes and facilitate the identification of alternative sustainable farming practices. The environmental analysis conducted so far, which focused on SOC and PDF indicators, is a preliminary step in understanding the ecosystem services associated with soil quality and biodiversity decline (Vidal-Legaz et al., 2016).

5. Conclusions

The present study evaluates the environmental performance of wheat cultivation in rotation with chickpea and lentils compared to the conventional monoculture system, aiming to produce wheat with a

lower environmental impact under Mediterranean conditions in Morocco. The results showed that crop rotations are the most environmentally friendly cropping systems for the majority of impact categories, regardless of the functional unit considered. However, trade-off problems were observed between functional units to the detriment of those systems with lower wheat yields when the productive functional unit is selected. In this sense, while the R1 (chickpea:wheat) and R2 (lentil:wheat) rotation systems outperform monoculture in terms of hectare-years (sharing a similar impact), R1 shows the worst environmental profile in ME and PDF per kg of wheat.

On a land management basis, no significant differences were identified between the cropping systems (R1, R2 and M) in terms of PDF. In contrast, crop rotations showed an improved SOC profile, suggesting additional ecosystem benefits associated with SOM (e.g., nutrient and water retention and climate change mitigation). Mineral fertilizer production and application appear to be the most critical aspects in all impact categories, except in WS, PDF and SOC, for which irrigation, land transformation and land occupation were the determining factor, respectively.

This study aims to contribute to more sustainable agriculture in Morocco and similar Mediterranean regions with valuable information. Future studies could focus on incorporating ecosystem services into the environmental assessment of such systems in order to obtain a more comprehensive assessment that can be used as a tool for guidance and decision-making.

CRedit authorship contribution statement

Sara Lago-Oliveira: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Hanane Ouhemi:** Data curation, Writing – review & editing. **Omar Idrissi:** Data curation, Writing – review & editing. **Maria Teresa Moreira:** Supervision, Writing – review & editing. **Sara González-García:** Funding acquisition, Investigation, Supervision, Writing – review & 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2024.100169>.

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