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Improving environmental sustainability of agriculture in Egypt through a life-cycle perspective

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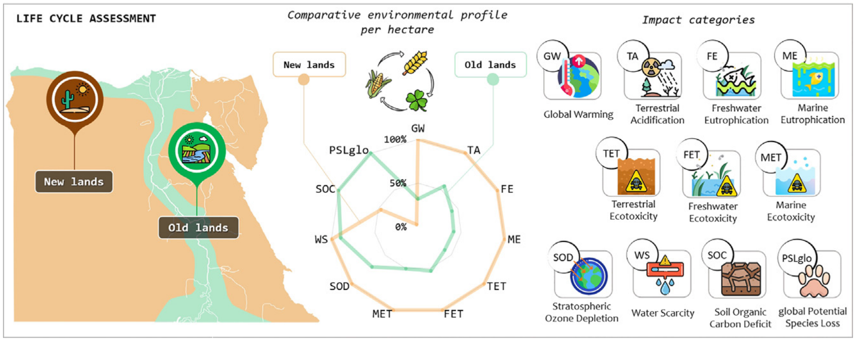
HIGHLIGHTS

- Agricultural practices on fertile and irrigated desert areas of Egypt are analyzed
- Crop rotation in fertile regions had higher environmental impact on most indicators
- Irrigation and emissions from N-fertilizer use are key environmental factors
- Biodiversity loss is predominantly driven by land transformation
- Soil organic content depletion is attributed to land use intensity

GRAPHICAL ABSTRACT



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ABSTRACT

Soil plays an essential role as a habitat, source of nutrients and support for vegetation. Promoting food security and environmental sustainability of agricultural systems requires an integrated approach to soil fertility management. Agricultural activities should be developed with preventive approaches aimed at avoiding or reducing negative impacts on the soil physicochemical and biological properties and the depletion of soil nutrient reserves. In this regard, Egypt has developed the Sustainable Agricultural Development Strategy to encourage environmentally friendly practices among farmers, such as crop rotation and water management, in addition to extending agriculture to desert areas, favoring the socio-economic development of the region. In order to evaluate the outcomes of the plan beyond quantitative data of production, yield, consumption and emissions, the environmental profile of agriculture in Egypt has been assessed under a life-cycle perspective in order to identify the associated environmental burdens and ultimately contribute to improving the sustainability policies of agricultural activity within the framework of a crop rotation system. In particular, a two-year crop rotation (Egyptian clover-maize-wheat) was analyzed in two distinct agricultural areas in Egypt: New Lands in desert regions and Old Lands along the Nile River, traditionally recognized as fertile areas due to the river alluvium and water availability. The New Lands had the worst environmental profile for all impact categories, except for Soil organic carbon deficit and Global potential species loss. Irrigation and on-field emissions associated with mineral fertilization were identified as the most critical hotspots of Egyptian agriculture. In addition, land occupation and land transformation were reported as the main drivers of biodiversity loss and soil degradation, respectively. Beyond these results, further research on biodiversity and soil quality indicators is needed to more accurately assess the environmental damage caused by the conversion of deserts into agricultural areas, given the species richness these regions hold.

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1. Introduction

In 2021, the number of people affected by hunger globally rose to 828 million (FAO et al., 2022). Food sovereignty associated with agricultural activities plays a key role in achieving food security, although it can also pose a serious threat if practiced in an unsustainable way. In particular, land use and degradation, high water and energy consumptions, as well as biodiversity loss are identified as elements contributing to the environmental burdens associated with this type of activities (Eugenio et al., 2018; IPCC, 2019a).

Moreover in a context of political instability, countries in Africa and the Middle East are among the most threatened by food shortages, supply chain disruptions and rising prices, and it is especially in these areas that the greatest efforts in the context of food sovereignty should be emphasized (ELD Initiative and UNEP., 2015; Ziadat et al., 2021). In particular, the pace of price increases for several key crops, particularly cereals (wheat, maize, barley and rice), has accelerated. In these countries, soil degradation already affects more than 45 % of the land, and crop yields are projected to undergo substantial declines (up to 80 % by 2025), due to water scarcity, high prices of seeds, fertilizers and energy, extreme weather events, and rising temperatures (ELD Initiative and UNEP, 2015; IPCC, 2019a; IFAD, 2021).

To ensure food and nutrition security on the planet, especially in the most vulnerable countries, a more sustainable and resilient agricultural model should consider crop rotation practices with the aim of improving agricultural yields while protecting the environment (European Environment Agency, 2020). These practices can improve crop protection against pests and diseases (especially those with short survival times) (SARE, 2020), and promote physical, chemical and biological fertility of the soil (Beillouin et al., 2021). Although these types of practices have been displaced by monoculture systems due to economic reasons (Balogh, 2021), monocultures require higher agrochemical inputs and deliver lower yields over the years; generally leading to lower profitability compared to rotations (Ouda et al., 2018; Beillouin et al., 2021).

Egypt is a North African country characterized by its low share of arable land per capita (0.03 ha), one of the lowest in the world (The World Bank, 2018). Like other countries in the region, Egypt relies on global markets for a large share of staple crops and it is experiencing difficulties in meeting food demand (World Food Programme, 2022). In the long term, the Egyptian Government has developed the Sustainable Agricultural Development Strategy (SADS) with the purpose of boosting agricultural production in a sustainable manner by 2030 (MALR, 2009). As part of the strategy, crop rotation practices are being promoted among farmers, as well as other key aspects, such as water management and the extension of agricultural lands to desert areas.

Life Cycle Assessment (LCA) is a standardized methodology widely used to measure potential environmental impacts in the agri-food sector (Almeida-García et al., 2022; Costa et al., 2020). LCA can analyze multiple environmental impacts throughout the life cycle of a production system and allows to detect those stages that contribute most to the environmental burdens. Climate change, ecotoxicity and acidification are among the most commonly analyzed impact categories in the agricultural sector (Alhashim et al., 2021; Costa et al., 2020). However, there are other key areas that are greatly affected by agricultural activities, such as biodiversity loss and soil quality, which are rarely considered in the assessment (Costa et al., 2020). Furthermore, despite the large proliferation of LCA studies in recent years, few LCA analysis have been conducted in Egypt, none of them related to the agri-food sector (Karkour et al., 2021). Understanding the environmental burdens of Egyptian agriculture, including those related to biodiversity loss and soil degradation, and how crop rotation affects the different cultivation areas in the country, could highly contribute to guide Egyptian policies aimed at developing a more sustainable agriculture. Accordingly, the main objective of this study will be to assess and compare the environmental performance of a rotation system cultivated in the two distinct regions of Egypt corresponding to the fertile and irrigated desert areas. On this basis, differences in environmental burdens are anticipated and measures can be proposed to improve the environmental profile of each scenario.

2. Material and methods

2.1. Description of the studied area

Egypt is characterized by a very small agricultural area (3 % of the total area) (Fig. 1), in which three zones can be distinguished (Ouda et al., 2018): Old Lands, found along the Nile Valley and the Delta, stand out for their high fertility; New Lands are fields recovered from the desert through governmental programs and private sector support; and the rainfed areas, located in the northern coast, are mainly used for livestock breeding due to their shallow depth and rocky characteristics.

The studied area encompasses both the Old Lands and the New Lands. These regions are characterized by an arid climate, with an average annual rainfall of 150 mm/year, and alkaline soils. While the soils of the Old Lands have a high organic matter and clay content (50 % clay), the organic matter content of the New Lands is low, and their texture is sandy (8 % clay). In addition, for historical reasons, the Old Lands are laid out in small agricultural plots and generally belong to a single farmer, while the New Lands are arranged in large fields owned by large companies.

2.2. Description of the crop rotation systems

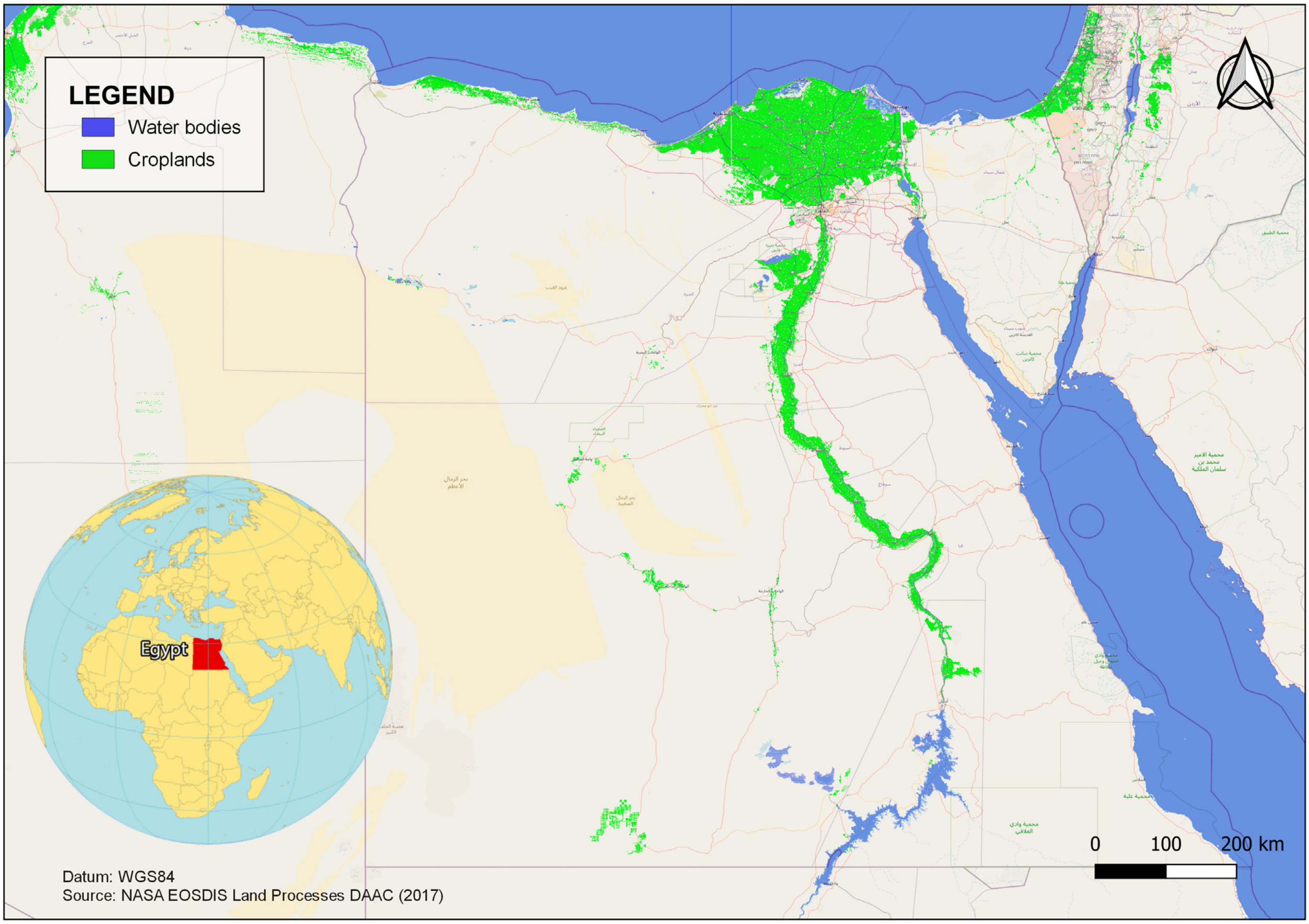
The agricultural system under study consists of spring wheat (*Triticum aestivum* L. and *Triticum durum* L.), maize (*Zea mays* L.), and Egyptian clover (*Trifolium alexandrinum* L.) arranged in a two-year rotation cycle (Fig. 2). In addition, it includes a short period of fallow between July and August. Both wheat species and maize are grown for human consumption, whereas Egyptian clover and wheat straw are destined to fodder production. They stand among the most cultivated crops in Egypt (FAO, 2014, 2022; Ouda et al., 2018), and therefore they have been selected as the target crops. The crops are cultivated following conventional farming practices, which are conducted in three main stages: soil conditioning, crop growth and harvesting. During soil conditioning, the field is prepared for sowing by performing tillage and pre-sowing fertilization activities, and ends with sowing. This is followed by the crop growth stage, which refers to a set of practices aimed at nurturing the crop through additional fertilization, irrigation and agrochemicals treatments. In the final stage, harvesting, agricultural products are collected for sale.

2.2.1. Crop rotation system in Old Lands

2.2.1.1. Egyptian clover cultivation. Egyptian clover production begins in September with soil tillage with a chisel plough, followed by mineral fertilization and sowing. Between May and June, the clover is harvested and used for forage production. Harvesting can be done manually or with a self-propelled mower. During the whole growing stage, the crop is irrigated with surface and groundwater by surface irrigation.

2.2.1.2. Maize cultivation. Maize cultivation begins in July, just after the clover has been harvested. Firstly, chisel ploughing is performed, continued by mineral fertilization and sowing. This is followed by an insecticide treatment. From September to November, maize is harvested manually and threshed, while the leftover straw is burned. As for all crops settled in Old Lands, maize is superficially irrigated using surface and groundwater.

2.2.1.3. Wheat cultivation. Between November and December, the field is prepared for wheat by chisel ploughing and fertilization, and two weeks later, wheat seeds are sown. During wheat growth, an herbicide treatment is applied. Towards May and June, wheat is harvested manually and threshed. All the straw produced is removed from the field and used for animal feeding. Surface water and groundwater is applied superficially along the growing season.



Datum: WGS84
Source: NASA EOSDIS Land Processes DAAC (2017)

Fig. 1. Geographical distribution of agricultural lands (green color) in Egypt. The cropland geolocation data was extracted from Xiong (2017).

All inventory data related to the crop rotation system in Old Lands (including input rates, diesel consumption, yields, etc.) are summarized in Tables S1–S3 of the Supplementary Material. In addition, a list of the manufacturers of fertilizers is given in Table S7.

2.2.2. Crop rotation system in New Lands

A similar agronomic schedule is followed in New Lands; however, with relevant differences, which are described below, as well as in Tables S4–S6 of the Supplementary Material.

2.2.2.1. Egyptian clover cultivation. The soil is prepared by disk ploughing two weeks before sowing Egyptian clover. The New Lands are fertilized through a fertigation technique, which uses irrigation to spread the inputs through a sprinkler. In late spring, the aerial biomass is harvested with a mower.

2.2.2.2. Maize cultivation. Immediately after clover cutting, the field is prepared with disk ploughing for planting maize. During maize growth, groundwater and several fertilizers are spread by sprinkler and drip

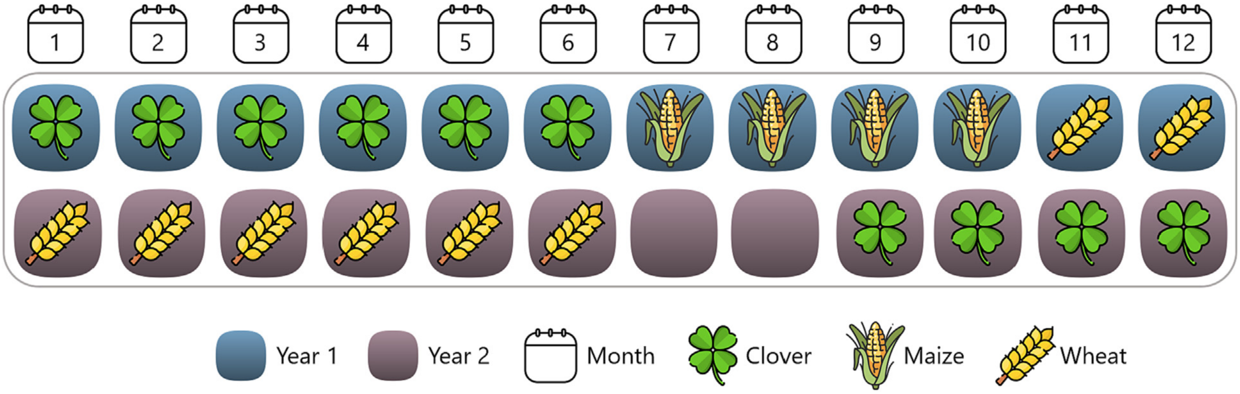


Fig. 2. Layout of the crop rotation system under study.

irrigation methods. In addition, the crop is treated with an insecticide using a sprayer machine. Finally, harvesting and threshing are carried out simultaneously by a combined machine, and alike in Old Lands, the straw produced is burned.

2.2.2.3. Wheat cultivation. Firstly, the land is prepared by disk ploughing before sowing wheat seeds. A set of various fertilizers are applied by sprinkler and drip fertigation. During growing stage, an herbicide treatment is also added to the crop with a sprayer machine. As in maize, wheat is collected and threshed with a combined machine. All the remaining straw is sold for animal fodder.

2.3. Life cycle assessment method

The present work follows the attributional Life Cycle Assessment (LCA) methodology, covering the 4 phases proposed by ISO standards 14040 and 14044: i) goal and scope definition, ii) life cycle inventory, iii) life cycle impact assessment and iv) interpretation.

2.3.1. Goal and scope definition

2.3.1.1. System boundaries. The system boundaries comprise from cradle to farm-gate (Fig. 3), including raw material extraction (e.g., fossil fuels and minerals), manufacture (e.g., seeds, mineral fertilizers, herbicides, insecticides, fungicides, and agricultural machinery), use, maintenance and end-of-life management of the machinery.

2.3.1.2. Functional unit and allocation. Since the main objective of the study is to assess and compare the environmental performance of the agricultural practices performed in two different regions, aiming to identify the best management and hotspots, a land-based functional unit was defined, in this case one hectare. Considering that the agricultural systems were analyzed as a whole (without distinguishing between agricultural products), no allocation procedure was performed.

2.3.2. Life cycle inventory

The life cycle inventory is composed of primary and secondary data. The primary data represent the foreground system (Fig. 3) and were mainly collected through interviews and surveys with local farmers and farming companies. The information obtained, corresponding to a total of 100 farmers and 12 companies, is summarized in Tables S1–S6 of the Supporting Material. In addition, primary data on emissions from the foreground system were estimated using different empirical models (Sections 2.3.2.1 and 2.3.2.2). The contribution of the machinery used on each farm was calculated by taking into account the weight, operating hours and useful life of each machine. The secondary data constituting the background system were obtained from the Ecoinvent® 3.8v database (Wernet et al., 2016).

2.3.2.1. Direct and indirect field emissions. On-field emissions were estimated based on fertilizers and phytosanitary products (herbicides, insecticides, fungicides) dosed to crops. To calculate direct and indirect nitrous oxides (N_2O) emissions, the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2019b) were adopted, using as emission factors those specifically reported for each type of fertilizer applied. All factors used in the calculation of on-field emissions, including the ones above, are listed in Table S8 of the Supplementary Material.

NH_3 and NO_2 emissions were calculated as reported by the European Environment Agency (EMEP/EEA, 2019). For NH_3 emissions, the fertilizer-specific factors were selected assuming a pH above 7 (Table S8), as for NO_2 emissions, an emission factor of 0.04 $kgNO_2 \cdot kg\ N^{-1}$ was considered for all fertilizers. In turn, nitrate leaching (NO_3^-) was determined following the model developed by Faist et al. (2009), and considering the

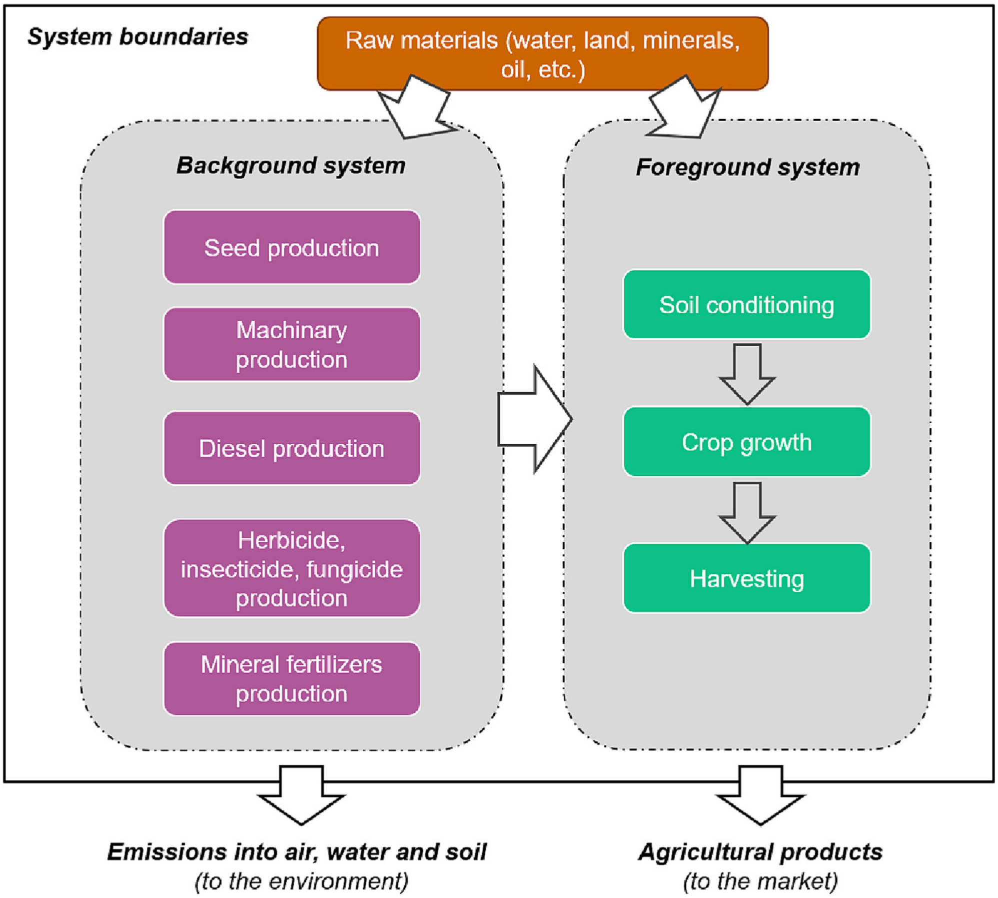


Fig. 3. System boundaries of the agricultural systems under study.

rooting depth of each crop (1.20 m for wheat, 0.30 m for Egyptian clover and 1.35 m for maize), as well as the clay content of the soil (around 50 and 8 % for crops grown in Old and New Lands, respectively). Moreover, phosphate emissions were computed with the SALCA-P model (Prasuhn, 2006), considering different emission factors depending on whether phosphate leached to groundwater or was discharged to surface water (Table S8). In addition, emissions related to plant protection products were calculated as defined in the PEFCR protocol (European Commission, 2018) (Table S8). Finally, CO_2 emissions from urea were determined following IPCC guidance (IPCC, 2019b).

2.3.2.2. Emissions from land-use change. Agricultural activities are the main drivers of land-use change (LUC) as a result of land occupation (Parra-Paitan and Verburg, 2022). LUC can be divided into direct land-use change (dLUC), referring to changes in soil carbon content that occur directly on the land used; and indirect land-use change (iLUC), which describes alterations occurring elsewhere (Schmidt et al., 2015). In the present study, only greenhouse gas (GHG) emissions related to iLUC were considered, as no return of residual biomass was adopted in the systems studied. Therefore, assuming that no changes in soil carbon content occurred at the field. Based on the biophysical model developed by Schmidt et al. (2015), a single country-specific emission factor was obtained for agricultural land-used per rotation system: 17 kg $CO_2eq\cdot ha^{-1}$. For its measurement, 1 $ha\cdot year^{-1}$ of arable land per rotation was regarded, in addition to a potential net primary production (NPP0) of 0.83 t $C\cdot ha^{-1}\cdot yr^{-1}$, and an overall average productivity of 6.11 t $C\cdot ha^{-1}\cdot yr^{-1}$.

2.3.3. Life cycle impact assessment

The environmental loads related to each crop area were quantified following midpoint and endpoint approaches. First, the next midpoint impact categories were assessed: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), and Marine Ecotoxicity (MET); and calculated with ReCiPe 2016 V1.06 Hierarchist Midpoint method World (2010) (Huijbregts et al., 2017). In addition to these common categories, Water Scarcity (WS), Soil Organic Carbon (SOC) Deficit, and global Potential Species Loss (PSLglo) were also estimated following their respective methods. Each of these impact categories was selected and assessed based on their recognition as the most relevant to agricultural systems (Costa et al., 2020; González-García et al., 2021).

Water Scarcity refers to the water availability after withdrawing the water required by the system under study. To assess it, the AWARE (Available WAter REmaining) method 1.04 was implemented (Boulay et al., 2018). Moreover, the SOC deficit and PSLglo were measured according to the (UNEP-SETAC Life Cycle Initiative, 2019a, 2019b). These indicators evaluate the impacts on soil and biodiversity, respectively, associated with land-use, which, although rarely assessed in LCA, mainly due to their complex pathways (Costa et al., 2020; Life Cycle Initiative, 2016; UNEP-SETAC Life Cycle Initiative, 2019a), are key aspects to be taken into account when conducting an environmental study in the agricultural sector. The SOC deficit was calculated using the updated model of Brandão and Canals (2013), while PSLglo was determined based on the countryside species-area relationship (SAR) model developed by Chaudhary et al. (2015), in combination with a vulnerability score (VS). The SAR model covers a total of 804 terrestrial ecoregions (Chaudhary and Brooks, 2018; Olson et al., 2001). The New Lands are part of the Sahara desert ecoregion (code: PA1327), while the Old Lands belong to the Nile Delta flooded savanna ecoregion (code: PA0904). The vulnerability score, it is a function of the number of endemism (i.e., species confined to a specific habitat) and the level of threat. It should be recognized that PSLglo is an endpoint category that reflects an ecosystem-level damage effect, in contrast to the other categories that represent changes in different environmental aspects. The environmental assessment and environmental evaluation were performed in SimaPro v9.4 software (PRé Sustainability, 2022) and Microsoft Excel® 365 MSO.

3. Results and discussion

A detailed analysis of the environmental performance of the New and Old Lands is presented below. First, a general comparison of the environmental impacts of the two regions is provided (Section 3.1.), followed by a more detailed examination of the environmental performance of the specific crops involved (Section 3.2.) and an in-depth analysis of the factors contributing to the environmental profile by impact category (Section 3.3.). In addition, key environmental factors are further discussed in Section 4.1. (irrigation), Section 4.2. (fertilization), and Section 4.3. (extension to new lands), as well as of the crop rotation regime versus monoculture (Section 4.4.). Finally, the study limitations are outlined in Section 4.5.

3.1. General comparison of the environmental profile between New and Old Lands

Fig. 4 depicts the comparative profile of rotations grown in New and Old Lands based on one hectare (functional unit). Regarding the absolute impact values, they are displayed in Table S9 of the Supplementary Material. The rotation cultivated on Old Lands presents the best environmental profile for nearly all impact categories. SOC deficit and PSLglo are the exception, for which New Lands rotation poses a higher performance. The global lower accomplishment of New Lands system is a consequence of the larger fertilization rates, along with the use of a pumped irrigation system (drip and sprinkler irrigation) as opposed to surface irrigation used on Old Lands. As a result, more fertilizers, diesel and electricity are consumed, as well as irrigation infrastructure, in New Lands (Tables S1–S6 of the Supplementary Material). In terms of WS, the slightly more critical impact in New Lands is due to the higher water expenditure (22,697 $m^3\cdot ha^{-1}$ and 20,349 $m^3\cdot ha^{-1}$ for New and Old Lands respectively).

This more intensive agricultural practices in the desert region helps to compensate for the lower fertility and less suitable conditions for agricultural activities, achieving yields close to those of the fertile areas (Old Lands) (Tables S1–S6). While the land-based functional unit is independent of yield, a mass-based functional unit tends to benefit higher yielding systems. As the Old Lands have slightly higher yields and produce less intensively, they would still be more sustainable if a mass-based functional unit were adopted.

Particularly notable is the difference within the PSLglo loads of both rotation systems, with the impact of Old Lands being 28 times greater than of New Lands. The Sahara desert (New Lands) holds higher species richness per unit area than Nile Delta flooded savanna (Old Lands) (Chaudhary and Brooks, 2018; MEA, 2005a), as well as a larger number of endemism (Chaudhary and Brooks, 2018; MEA, 2005a). As the more endemic species, the higher the VS (MEA, 2005a), one might expect heavier burdens on New

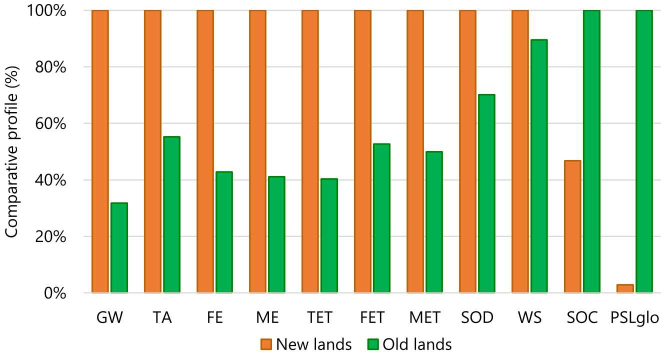


Fig. 4. Comparative environmental profile of New and Old Lands rotations per hectare and in terms of eleven impact categories. GW: global warming; TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; TET: terrestrial ecotoxicity; FET: freshwater ecotoxicity; MET: marine ecotoxicity; SOD: stratospheric ozone depletion; WS: water scarcity; SOC: soil organic carbon depletion potential; PSLglo: global potential species loss.

Lands. However, Chaudhary et al. (2015) states that regions with a smaller proportion of natural habitats face a higher biodiversity damage factor than areas with larger natural ranges. This is the case for Old Lands, which have been heavily converted due to increased land-use pressures operating in the area to meet human needs (MEA, 2005b). In addition, Old Lands require a longer regeneration time to recover (reported by Chaudhary and Brooks (2018) as 37 % higher). Because of this, Old Lands have higher characterization factors, ultimately leading to greater potential damage to biodiversity.

From a disaggregated taxonomic perspective (Fig. 5), it can be seen that biodiversity damage is not inflicted equally on all taxonomic groups, with mammals being the most threatened taxa regardless of region. As for the remaining taxonomic groups, plants emerge as the second most threatened taxa in the Old Lands, while in the New Lands the damage is distributed in decreasing order among birds, reptiles and plants. According to Chaudhary et al. (2015), the rationale for these findings is mainly explained by the proportion of threatened endemic species, for which mammals have a higher percentage compared to the other terrestrial taxa. As also detected by Semenchuk et al. (2022), amphibians stand among the taxa with the lowest species loss.

A more in-depth analysis of the specific factors causing the different levels of threat among taxonomic groups is beyond the scope of the present study. Nonetheless, it is noteworthy to briefly acknowledge the variety of intrinsic traits connected to the degree of extinction risk that species exhibit in response to land-use pressures. For instance, survival of terrestrial mammals is particularly influenced by body size, habitat coverage, and population density (Lacambra, 2016). In line with this, mammals with large proportions are severely affected by changes in land use (Magioli et al., 2021). As Durant et al. (2014) reports, large herbivores living in the Sahara desert, such as Dama gazelle and *Addax nasomaculatus* (both critically endangered species), require vast areas to find temporary rainfall reservoirs and avoid overgrazing. If these vast areas are even partially converted for human purposes, these taxa could be substantially compromised.

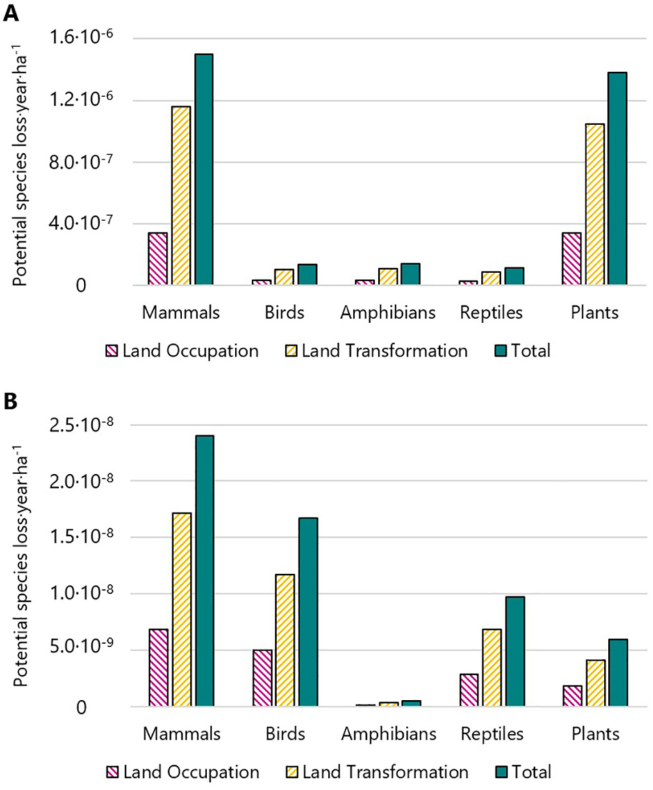


Fig. 5. Disaggregation of the biodiversity endpoint into 5 terrestrial taxa (mammals, birds, amphibians, reptiles and plants). A) Old Lands scenario. B) New Lands scenario.

Conversely, there are species with a limited geographic range that are also very likely to go extinct in response to land-use transformation, as is the case for plants (Staude et al., 2020).

In terms of SOC depletion potential, crop rotation offers an appreciably greater impact in Old Lands than in New Lands (68 % and 32 % respectively). This midpoint indicator measures changes in soil organic carbon content driven by land-use and land-use change stressors, and eventually, the impact on biomass productivity (endpoint) (Brandão et al., 2012). In the present study, the same land use specifications were assumed for both regions in accordance with IPCC guidelines (long-term cultivated, full tillage and high inputs without manure) (IPCC, 2019). Thus, the disparity between the regions lies in the original soil organic carbon content, for which New Lands represent a lower amount (1 kg·m^{-2}) compared to Old Lands (2.4 kg·m^{-2}). In consequence, under similar land use conditions, Old Lands are more susceptible to organic carbon losses than New Lands.

SOC is an important component of soil organic matter (SOM). At the same time, SOM is a key element within soils with direct influence on biomass productivity (Brandão et al., 2012). Consequently, a reduction in SOC due to land-use drivers can cause a decrease.

in soil productivity. In this sense, naturally fertile areas, such as Old Lands, can lose their productive capacity and, therefore, impair agricultural yields when intensive practices are implemented (full tillage, removal of residual biomass and high doses of fertilizers, among others).

3.2. Comparison between affected crops

Focusing on the crops involved in the rotation, maize represents the main contributor to most of the impact categories (GW, TA, FE, ME, TET, FET, MET, SOD) regardless of the agricultural region (Fig. 6). In this sense, maize is the crop with the highest fertilizer and water input requirements. As an example, 1200 kg·ha^{-1} of fertilizer is applied to maize in Old Lands versus 495 and 500 kg·ha^{-1} to clover and wheat respectively. In addition, maize cultivation is more mechanized than clover cultivation, as additional field operations, such as insecticide treatment and threshing, are carried out in its case. Nonetheless, maize stands as the least damaging crop in terms of PSLglo and SOC deficit, following by wheat and clover. The reason is that, as PSLglo and SOC deficit burdens are mainly derived from the foreground system (between 72 % and 98 % of the total), the area directly used for agriculture, together with the harvesting period of each crop, determines PSLglo variations among crops. In this way and taking into account that all crops within the rotation use the same crop area, maize had a lower impact on biodiversity due to the lower cultivation period (5, 9 and 10 months for maize, wheat and clover, respectively).

Regarding clover and wheat, a minor share of impact responsibilities is observed between both crops for almost all impact categories despite the region analyzed. It is especially relevant the environmental benefit that clover brings to rotations in virtue of its high nitrogen-fixing capacity (180 kg·ha^{-1}) (Agriculture and Horticulture Development Board, 2020), particularly in New Lands (−27 % in ME). This positive effect of legumes on the environment has been widely recognized in previous studies (Costa et al., 2020).

3.3. Parameters contributing to the environmental profile

Fig. 7 displays the environmental profiles of New and Old Lands rotations based on the different contributing parameters. Irrigation is solely responsible for the WS results in both scenarios, due to the large amount of water used for this agronomic practice.

Concerning the rotation system of New Lands, irrigation is also the main factor shaping most of the remaining environmental loads (GW, FE, TET, FET, MET). Its contribution is especially notable in GW (62 %) due to the CO_2 emissions caused by diesel combustion during irrigation, and indirectly, by the combustion of gas and gasoline used as fuels (BP, 2022). In addition, diesel production and irrigation equipment (pumps, pipes) releases phosphate into the water and depletes oxygen levels, which subsequently causes FE loads. Likewise, equipment manufacturing also delivers copper

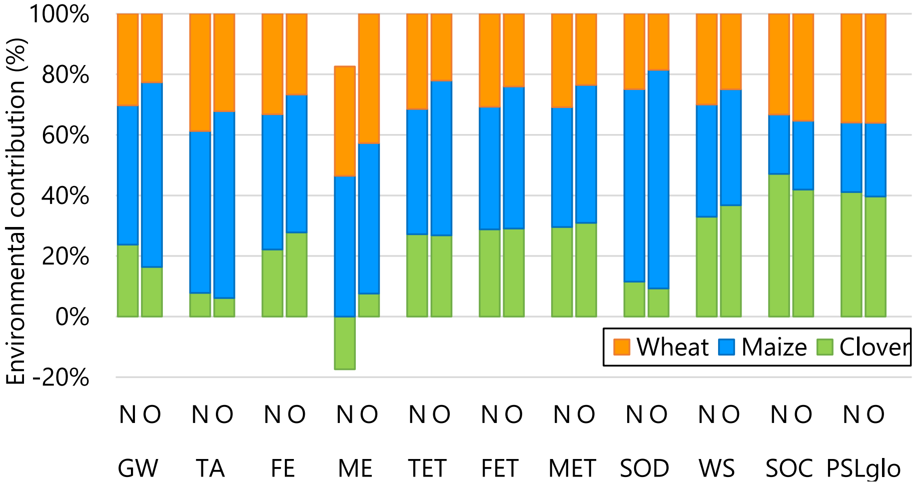


Fig. 6. Crops contribution to the environmental profile of the rotation systems. N: New Lands scenario; O: Old Lands scenario.

into soil and water, which are accounted in toxicity categories. Additionally, another factor influencing the environmental profile of New Lands rotation are on-field emissions, especially in TA, ME and SOD. On-field emissions comprise discharges to air, water and soil derived from fertilization, diesel combustion, weeds and pests' treatments, and CO_2 emissions from iLUC (17.12 kg CO_2 eq. per rotation system). In this case, nitrogen-based emissions (NH_3, NO_3^-, N_2O) from mineral fertilization are the major responsible. (See Tables S10 and S11 of the Supplementary Material for detailed discussion of emission sources and their contribution to the impact).

Environmental constraints in Old Lands are predominantly determined by on-field emissions, followed by fertilizer production and irrigation activities. GW, TA, ME and SOD are the impact categories most influenced by emissions in the field (53 %, 83 %, 90 % and 96 % respectively), mainly due to the application of N-based fertilizers. A similar trend can be identified for New Lands. Regarding fertilizer production, several elements are discharged during their manufacture, among which phosphate is the most notable within FE loads, while copper emissions are more significant in TET and FET. Finally, water toxicity categories (FET and MET) are also determined by irrigation due to copper leaching. As accounted for in the Old Lands scenario, these emissions are caused by the manufacture of the irrigation equipment.

With respect to PSLglo and SOC deficit, impacts are driven by land occupation and transformation stressors occurring on agricultural land (foreground system) or elsewhere (background system). As mentioned above, the foreground system is responsible for practically all PSLglo and SOC deficit impact. In a more detailed analysis, land transformation can be identified as the main factor triggering biodiversity loss (Figs. 5 and 7). In line with this results, Semenchuk et al. (2022) found that 3 quarters of the biodiversity damage are due to transformations of natural habitat ecosystems, and that the remaining impact was related to the intensity used. Meanwhile, SOC deficit is mainly caused by land occupation (and associated intensity used) (Fig. 7), as also identified in Brandão and Canals (2013).

With reference to seed and agrochemical (insecticides and herbicides) production as well as field operations (sowing, threshing, and so forth), they have a negligible contribution to global environmental burdens (up to 8 %) regardless of the impact category and scenario assessed. However, it is interesting to note the predominant contribution of seed production (through its associated land use/transformation pressures) to the PSLglo and SOC deficit impacts on the background system (see Figs. S1–S2 in the Supplementary Material).

4. Further considerations and recommendations

Once the environmental burdens have been described, further analysis involving several key environmental and social issues that Egypt is currently facing will be conducted to advance possible solutions and improvements towards a more sustainable agriculture.

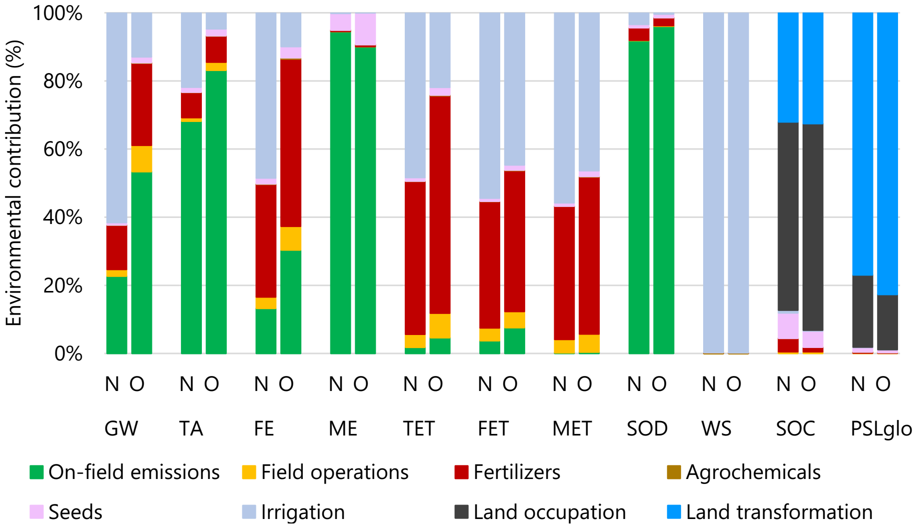


Fig. 7. Process contribution to the environmental profile of the New Lands scenario (N) and the Old Lands scenario (O).

4.1. Irrigation

Water consumption has been rarely assessed in legume rotations under an irrigation regime (Costa et al., 2020), despite the fact that freshwater is primarily withdrawn for irrigation (UN Water, 2021). In the present study, water scarcity has been analyzed using AWARE model. This model uses characterization factors (CFs) that range between 0.1 and 100. Where a factor of 1 represents the world average of water remaining after water withdrawal by both humans and ecosystems, and values higher than 1 correspond with a lower level of remaining water than world average, with values up to 100 times lower (CF = 100). Such high figures are present in areas where water withdrawal exceeds natural water renewal (no water is remaining in the area after withdrawal). Accordingly, the high CF values among all Egypt (for instance, 94 and 100 m^3 world eq. per m^{-3} of water consumed for New and Old Lands, respectively) (Boulay et al., 2018) reveal the critical problematic that the country is facing in relation to water scarcity. As informed by United Nations Development Programme and Ministry of Planning and Economic Development (2021), Egyptian population does not reach the minimum amount of water required to meet basic human needs (around 640 in face of 1000 $m^3 \cdot year^{-1}$ baseline); a problem that is expected to worsen due to climate change. In this context, unplanned irrigation practices are likely to aggravate water scarcity and food insecurity (UNESCO et al., 2019). Moreover, irrigation requires most of the diesel and energy consumed in the farming systems, as also found in former studies (Xu et al., 2020), which contributes to GW impact. Apart from that, watering can also cause other disturbances, such as soil salinization. Therefore, a more efficient irrigation system, as well as a cleaner energy production, could alleviate the whole environmental profile.

In this regard, Fotia et al. (2021) evaluated olive production under rainfed, conventional and smart irrigation scenarios in a Mediterranean country, and they observed that smart irrigation reduced over 43 % the impact associated to irrigation activities due to the lower water and energy consumption (compared to conventional irrigation). Canaj et al. (2021) also achieve similar outcomes, with an average reduction of water and energy of 38 % and associated environmental benefits. This, among other smart irrigation devices, are acknowledged by ITU (2021) as good agricultural practices; which apart from irrigation, also allow managing pests and fertilization in a more efficient approach (ITU, 2021).

On another hand, several authors proposes irrigation with reclaimed water as alternative to groundwater with improved environmental results, especially in terms of water depletion (Azeb et al., 2020; Pfister et al., 2009). In addition, by watering with reclaimed water agricultural systems can also benefit from their higher nutrient content (N, P_2O_5, K_2O), and avoid occasional alterations found in groundwater composition due to sea water intrusions and/or human activities (Azeb et al., 2020).

Concerning the energy consumed by irrigation, United Nations Economic Commission for Europe (UNECE) performed an LCA analysis of different alternatives of electricity generation (UNECE, 2021). Their findings showed a better environmental profile of renewable energies (solar, wind and hydropower) for GW and water consumption rather than natural gas (a predominated source of Egyptian electricity mix (55 %) (BP, 2022). However, they also noticed higher burdens of land occupation associated to photovoltaic panels, and analogous constraints in relation to resource depletion. Thus, although no definitive conclusions can be extracted from the study, it outlines different options for reducing electricity-related environmental constraints.

4.2. Fertilization

On-field emissions owing to fertilization exceled as major hotspot for Old Lands scenario, and as the second largest flashpoint in New Lands, mainly due to high fertilization rates. These outcomes are in line with Global Change Data Lab (2021) figures, which reveal that Egypt stands as one of the countries that more overfertilize in the world, along with having one of the lowest nitrogen use efficiencies. This situation can be amended in several ways. In the first place, legumes are well known for delivering nitrogen to the subsequent crops due to their nitrogen fixation ability. Considering that the rotation system under study includes a leguminous crop (Egyptian clover), farmers could reduce fertilization doses without impairing crop yields (Zhao et al., 2022). Moreover, sustainable land management practices can also contribute to reduce fertilization doses meanwhile increasing soil quality in the long term (Ukaew et al., 2015; EIP-AGRI, 2016). Additionally, these practices can prevent from soil erosion and fertilizers lixiviation caused by irrigation (EIP-AGRI, 2015). Examples of such sustainable practices are reduced or no-tillage and returning a portion of the harvested biomass to the soils. The latter could be applied directly with the straw produced in the scenarios studied, which farmers currently burn. Taken together, these practices can alleviate environmental burdens, and even have a positive effect. This is the case with the carbon credits that are often achieved by returning excess biomass to the fields (González-García et al., 2021; Rebolledo-Leiva et al., 2022).

4.3. Agricultural extension to New Lands

The land use change of desert areas for agricultural use not only results in more fertile cultivation areas where erosion is reduced, but from a social and economic point of view, agricultural practices in the desert provide food and income, thus potentially improves the living conditions of underprivileged groups. In this respect, the government of Egypt is promoting agricultural expansion in desert regions (New Land) aiming at addressing food shortages. However, considering the results obtained in the present study, this solution may cause severe environmental damage, such as those discussed above, and even lead to a larger food crisis (Eugenio et al., 2018). In addition to the impact categories for which New Lands ranked as the worst-case scenario, the results suggest that the desert ecoregion is also highly susceptible to anthropogenic stressors, along with Old Lands, especially to land transformation and consequent habitat loss. With this in mind, further expansion of agricultural activities in these areas may lead to a notable loss of species (Durant et al., 2014).

4.4. Advantages of crop rotations over monoculture regimes

Crops grown in rotation are known to produce higher yields than monocultures regardless of the crop grown (Gan et al., 2015). Sindelar et al. (2016) reported yield increments of 18 % and 23 % for sorghum and maize, respectively, when cultivated in rotation. Chahal et al. (2021) also showed similar results, with yield increments ranging from 16 % to 29 %, for maize-based rotations. This yield increase has proven to be even greater when a legume is included in the rotation (Zhao et al., 2022), as it is the case in the crop rotation system studied here, and is independent of the pedoclimatic region (Zhao et al., 2022). Moreover, alternating crops with a legume contribute to reducing the amount of fertilization applied due to their ability to fix atmospheric nitrogen in the soil (Köpke and Nemecek, 2010), which, apart from its clear economic advantage, notably reduces the impacts related to the production and application of fertilizers (a major hotspot in the agricultural cultivation). In this sense, Almeida-García et al. (2022) reported the worst performance for wheat-based monoculture systems compared to the rotations in all impact categories. Similarly, MacWilliam et al. (2014) observed an overall improvement in the environmental profile of oilseed production when pea and lentil were introduced. In addition, Paramesh et al. (2023) reported an 81 % increase in GHG emissions in continuous rice cultivation compared to a rice-pea rotation. In line with Zhao et al. (2022), the reduction of the fertilizer dose applied in legume-based rotations promotes optimal agronomic performance in these agroecosystems, as they observed through a meta-analysis of 462 field trials that the influence of legumes on yields was enhanced in low fertilization regimes.

Crop rotation is considered by FAO (2022) a key strategy towards a sustainable agriculture, which enhanced soil quality by increasing its organic carbon content (e.g., Liu et al. (2020) reported an increment from 10.3 $g \cdot kg^{-1}$ to 11.2 $g \cdot kg^{-1}$), improving its structure (Zhang et al., 2022) and stimulating its microbial activity (Tiemann et al., 2015). In addition, Beillouin et al. (2021) underline the beneficial effect crop rotations have on biodiversity pools based on a meta-analysis conducted of 5.156 field experiments in 85 countries. The choice of crops and their sequence in the rotation are crucial to obtaining all the potential environmental and agronomic benefits mentioned here (Nemecek et al., 2015). For example, a rotation of crops with different requirements will result in a more efficient use of nutrient inputs, so that a smaller proportion is lost through leaching (SARE, 2020).

4.5. Study limitations

4.5.1. Global potential species loss

The global potential species loss (PSLglo) indicator is based on the empirical SAR (Species-Area Relationship) model and represents species loss due to land use and conversion. The indicator can be expressed on a regional scale or weighted with vulnerability scores to translate regional species loss into global extinction (permanent loss). This indicator is geographically specific, providing characterization factors for 804 ecoregions, and differentiates between six land use types (annual crops, permanent crops, pasture, urban, extensive forestry and intensive forestry) and three land use intensities (minimal, light and intense).

This is currently the method recommended by the UNEP-SETAC Life Cycle Initiative (2019a) for assessing impacts on biodiversity, although it is not without its limitations, which require consideration. The first is on land use types, as it includes the main types but lacks the granularity to include different management practices such as organic farming or crop diversification strategies (e.g., crop rotation). Furthermore, the vulnerability scores used to calculate global extinction are based on the IUCN Red List, which currently only covers mammals, amphibians and birds. Taxa- and region-unspecific factors are used instead for the remaining taxa (plants and reptiles), resulting in negligible differences between land use intensities for cropland and pasture, as noted by Chaudhary and Brooks (2018). None of these limitations affect the main conclusions of this work, as both scenarios are compared under the same assumptions (e.g., cropland, high intensity). However, comparisons with other systems under different management intensities may lead to misinterpretations.

Finally, in addition to land-use and land-use change pressures, there are other important drivers of biodiversity loss that are not taken into account. This is the case of temperature rises, water eutrophication, noise, invasive species, salinity and drying of water reservoirs, among others (Barbarossa et al., 2021; Curran et al., 2011; Winter et al., 2017). The UNEP-SETAC Life Cycle Initiative (2019a) also calls for the inclusion of the effects of habitat fragmentation on biodiversity loss. The development of impact pathways for these drivers and their inclusion in the assessment could change the results here obtained, in addition to enriching the outcomes.

4.5.2. Soil organic carbon deficit

As with PSLglo, the soil organic carbon (SOC) deficit developed by Brandão and Canals (2013), is currently considered the best option for measuring the impact on soil quality (UNEP-SETAC Life Cycle Initiative, 2019b). It relies on changes of soil carbon content over time, which in terms of UNEP-SETAC Life Cycle Initiative (2019b), represents soil functions simply and comprehensively. The indicator provides climate-specific factors with global coverage and is compatible with the land use flows of the LCI (UNEP-SETAC Life Cycle Initiative, 2019b). SOC changes are calculated according to IPCC (2019a, 2019b, 2019c) guidelines with the range of options it offers: ten climate regions (polar wet/dry, warm temperate dry/wet, etc.), six soil types (spodic, volcanic, sandy, etc.) and different management conditions according to tillage, land use and input intensity. As already pointed out by Piastrellini et al. (2015), the variety of management conditions provided by the IPCC is limited. For example, it does not distinguish between rainfed and irrigated regimes, nor does it take into account the specific proportions of residual biomass that could be returned to the field. Since the present study aims to compare systems under the same broad management conditions (irrigated, crop rotation) and residual biomass is either burned or sold as fodder, results are not affected by these limitations. However, comparisons with other systems with different agricultural regimes and/or cropping patterns may generate inaccurate insights.

Furthermore, analyzing other drivers of soil degradation, such as soil compaction and chemical pollution, through linking related LCI flows (hours of machinery used in the field and amount of fertilizer applied) to the impact on soil quality, would be highly advisable and would allow for granularity in the analysis. In addition, although SOC is representative of several soil functions, it lacks a link to some key aspects of soil quality such as erosion and soil salinity. Therefore, additional indicators or an integration of this indicator are desirable. One final limitation that deserves attention is that the effect of land transformation is modelled assuming a linear recovery, which is considered too simplistic by experts and should be re-examined (UNEP-SETAC Life Cycle Initiative, 2019b).

Understanding the critical points explored above (irrigation, fertilization, land use and land transformation) can benefit many stakeholders. First and foremost, farmers who would benefit from higher yields while safeguarding natural resources (mainly soil, water and biodiversity). Policy makers should be involved in developing more effective policies to achieve agricultural sustainability and alleviate water scarcity in the countries. Finally, the scientific community is also concerned, as the present study lays the groundwork for further evaluation of alternative agricultural practices aimed at alleviating environmental burdens in the Egyptian context.

5. Conclusions

The present study assesses the environmental performance of a crop rotation system (Egyptian clover, maize, and spring wheat) in two distinct agricultural regions of Egypt (New and Old Lands). The results show heavier environmental burdens in New Lands cultivation in comparison to Old Lands, suggesting that environmental profiles vary according to the characteristics (edaphic, climatic, hydrologic, etc.) of the location. The more intensive agriculture practices adopted in New Lands (mainly fertilization and irrigation) to overcome the lack of fertility and ensure similar yields to those in the Old Lands may have a significant impact on the local biodiversity and soil quality. Given that New Lands are territories hosting large pristine habitats that attract special attention to be partially converted into agricultural fields, evaluating such impacts are of particular importance. However, this will require future refinement of biodiversity and soil quality indicators in an effort to achieve a deeper and more representative level of understanding of agriculture-related burdens. Extending the analysis to technical-economic aspects could also be very valuable.

CRediT authorship contribution statement

Sara Lago-Olveira: Investigation, Methodology, Software, Writing, Visualization. Sherif R.M. El-Areed: data collection and reviewing. Maria Teresa Moreira: Supervision, writing, reviewing and editing. Sara González-García: Supervision, Investigation, funding acquisition, reviewing and editing.

Data availability

The data are available in the Supplementary Material

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

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References

Agriculture and Horticulture Development Board, 2020. Establishing and Growing Clover.

Alhashim, R., Deepa, R., Anandhi, A., 2021. Environmental impact assessment of agricultural production using LCA: a review. Climate 9, 164. https://doi.org/10.3390/cli9110164.

Almeida-García, F., Lago-Olveira, S., Rebolledo-Leiva, R., González-García, S., Teresa Moreira, M., Ruíz-Nogueiras, B., Pereira-Lorenzo, S., 2022. Growing Triticum aestivum landraces in rotation with Lupinus albus and fallow reduces soil depletion and minimises the use of chemical fertilisers. Agriculture 12, 905. https://doi.org/10.3390/agriculture12070905.

Azeb, L., Hartani, T., Aitmouheb, N., Pradeleix, L., Hajjaji, N., Aribi, S., 2020. Life cycle assessment of cucumber irrigation: unplanned water reuse versus groundwater resources in Tipaza (Algeria). J. Water Reuse Desalin. 10, 227–238. https://doi.org/10.2166/wrd.2020.015.

Balogh, A., 2021. The rise and fall of monoculture farming [WWW Document]. Horizon. EU Res. Innov. Mag. Eur. Comm. URL https://ec.europa.eu/research-and-innovation/en/horizon-magazine/rise-and-fall-monoculture-farming (accessed 9.14.22).

Barbarossa, V., Bosmans, J., Wanders, N., King, H., Bierkens, M.F.P., Huijbregts, M.A.J., Schipper, A.M., 2021. Threats of global warming to the world's freshwater fishes. Nat. Commun. 12, 1701. https://doi.org/10.1038/s41467-021-21655-w.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., Makowski, D., 2021. Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob. Chang. Biol. https://doi.org/10.1101/2020.09.30.320309.

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. 23, 368–378. https://doi.org/10.1007/s11367-017-1333-8.

BP, 2022. BP Statistical Review of World Energy 2022. BP Statistical Review of World Energy, London.

Brandão, M., Canals, L.M., 2013. Global characterisation factors to assess land use impacts on biotic production. Int. J. Life Cycle Assess. 18, 1243–1252. https://doi.org/10.1007/s11367-012-0381-3.

Brandão, M., Milà i Canals, L., Clift, R., 2012. Food, Feed, Fuel, Timber or Carbon Sink? Towards Sustainable Land Use. SpringerBriefs in Environmental Science. Springer Netherlands, Dordrecht https://doi.org/10.1007/978-94-024-2099-9.

Canaj, K., Parente, A., D'Imperio, M., Boari, F., Buono, V., Toriello, M., Mehmeti, A., Montesano, F.F., 2021. Can precise irrigation support the sustainability of protected cultivation? A life-cycle assessment and life-cycle cost analysis. Water 14, 6. https://doi.org/10.3390/w14010006.

Chahal, I., Hooker, D.C., Deen, B., Janovicek, K., Van Eerd, L.L., 2021. Long-term effects of crop rotation, tillage, and fertilizer nitrogen on soil health indicators and crop productivity in a temperate climate. Soil Tillage Res. 213, 105121. https://doi.org/10.1016/J.STILL.2021.105121.

Chaudhary, A., Brooks, T.M., 2018. Land use intensity-specific global characterization factors to assess product biodiversity footprints. Environ. Sci. Technol. 52, 5094–5104. https://doi.org/10.1021/acs.est.7b05570.

Chaudhary, A., Verones, F., De Baan, L., Hellweg, S., 2015. Quantifying land use impacts on biodiversity: combining species-area models and vulnerability indicators. Environ. Sci. Technol. 49, 9987–9995. https://doi.org/10.1021/acs.est.5b02507.

Costa, M.P., Chadwick, D., Saget, S., Rees, R.M., Williams, M., Styles, D., 2020. Representing crop rotations in life cycle assessment: a review of legume LCA studies. Int. J. Life Cycle Assess. 25, 1942–1956. https://doi.org/10.1007/s11367-020-01812-x.

Curran, M., de Baan, L., De Schryver, A.M., van Zelm, R., Hellweg, S., Koellner, T., Sonnemann, G., Huijbregts, M.A.J., 2011. Toward meaningful end points of biodiversity in life cycle assessment. Environ. Sci. Technol. 45, 70–79. https://doi.org/10.1021/es101444k.

Durant, S.M., Wacher, T., Bashir, S., Woodroffe, R., De Ornellas, P., Ransom, C., Newby, J., Abáigar, T., Abdelgadir, M., El Alqamy, H., Baillie, J., Beddiaf, M., Belbachir, F., Belbachir-Bazi, A., Berbash, A.A., Bemadjim, N.E., Beudels-Jamar, R., Boitani, L., Breitenmoser, C., Cano, M., Chardonnet, P., Collen, B., Cornforth, W.A., Cuzin, F., Gerngross, P., Haddane, B., Hadjeloum, M., Jacobson, A., Jebali, A., Lamarque, F., Mallon, D., Minkowski, K., Monfort, S., Ndoassal, B., Niagate, B., Purchase, G., Samaïla, S., Samna, A.K., Sillero-Zubiri, C., Soultan, A.E., Stanley Price, M.R., Pettorelli, N., 2014. Fiddling in biodiversity hotspots while deserts burn? Collapse of the Sahara's megafauna. Divers. Distrib. 20, 114–122. https://doi.org/10.1111/ddi.12157.

ELD Initiative & UNEP, 2015. The economics of land degradation in Africa. Benefits of Action Outweigh the Costs: A Report of ELD Initiative.

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

Eugenio, N.R., McLaughlin, M., Pennock, D., 2018. Soil Pollution. A Hidden Reality Rome.

European Commission, 2018. PEFCR Guidance Document - Guidance for Product Environmental Footprint Category Rules (PEFCRs). PEFCR Guid. Doc. p. 238.

European Environment Agency, 2020. Agriculture and the Green Economy.

Faist, M., Zah, R., Reinhard, J., 2009. Sustainable quick check for biofuels (SQCB): a web-based tool for streamlined biofuels' LCA. Environ. Informatics Ind. Environ. Prot. Concepts, Methods Tools. 1, pp. 297–303.

FAO, 2014. Egyptian clover (*Trifolium alexandrinum*). King of Forage Crops. FAO, Cairo.

FAO, 2022. FAOSTAT. Food and agriculture data [WWW Document]. URL (accessed 8.30.22) https://www.fao.org/faostat/en/#data.

FAO, IFAD, WFP, WHO, 2022. The state of food security and nutrition in the world 2022. Purposing food and AGricultural Policies to Make Healthy Diets More Affordable.

Fotia, K., Mehmeti, A., Tsirogiannis, I., Nanos, G., Mamolos, A.P., Malamos, N., Barouchas, P., Todorovic, M., 2021. Lca-based environmental performance of olive cultivation in northwestern Greece: from rainfed to irrigated through conventional and smart crop management practices. Water (Switzerland) 13. https://doi.org/10.3390/w13141954.

Gan, Y., Hamel, C., O'donovan, J.T., Cutforth, H., Zentner, R.P., Campbell, C.A., Niu, Y., Poppy, L., 2015. Diversifying crop rotations with pulses enhances system productivity. Nat. Publ. Gr. https://doi.org/10.1038/srep14625.

Global Change Data Lab, 2021. Can we reduce fertilizer use without sacrificing food production?. [WWW Document]. Our World Data. URL https://ourworldindata.org/reducing-fertilizer-use (accessed 10.30.22)

González-García, S., Almeida, F., Moreira, M.T., Brandão, M., 2021. Evaluating the environmental profiles of winter wheat rotation systems under different management strategies. Sci. Total Environ. 770, 145270. https://doi.org/10.1016/j.scitotenv.2021.145270.

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

IFAD, 2021. What Can Smallholder Farmers Grow in a Warmer World?

Intergovernmental Panel on Climate Change (IPCC), 2019a. N2O emissions from managed soils, and Co2 emissions from lime and urea application. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Intergovernmental Panel on Climate Change (IPCC), 2019b. Food security. Food Secur. Clim. Chang. L. an IPCC Spec. Rep. Clim. Chang. Desertif. L. Degrad. Sustain. L. Manag. food Secur. Greenh. gas fluxes Terr. Ecosyst, pp. 437–550.

Intergovernmental Panel on Climate Change (IPCC), 2019c. Cropland, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

ITU, F.A.O., 2021. Digital Excellence in Agriculture in Europe and Central Asia Good Practices in the Field of Digital Agriculture Stocktaking Report.

Karkour, S., Rachid, S., Maaoui, M., Lin, C.-C., Itsubo, N., 2021. Environments Status of Life Cycle Assessment (LCA) in Africa. https://doi.org/10.3390/environments8020010.

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

Lacambra, E.P., 2016. Spatial Patterns of Vulnerability in Terrestrial Mammals. Socioeconomic, Land Use and Species-Specific Correlates of Extinction Risk at a Global Scale. Pablo de Olavide University.

Life Cycle Initiative, 2016. Global Guidance for Life Cycle Impact Assessment Indicators. Vol. 1.

Liu, K., Bandara, M., Hamel, C., Knight, J.D., Gan, Y., 2020. Intensifying crop rotations with pulse crops enhances system productivity and soil organic carbon in semi-arid environments. F. Crop. Res. 248, 107657. https://doi.org/10.1016/J.FCR.2019.107657.

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

Magioli, M., Ferraz, K.M.P.M. de B., Chiarello, A.G., Galetti, M., Setz, E.Z.F., Paglia, A.P., Abrego, N., Ribeiro, M.C., Ovaskainen, O., 2021. Land-use changes lead to functional loss of terrestrial mammals in a Neotropical rainforest. Perspect. Ecol. Conserv. 19, 161–170. https://doi.org/10.1016/J.PECON.2021.02.006.

MALR, 2009. Sustainable Agricultural Development Strategy towards 2030 (SADS 2030).

Millennium Ecosystem Assessment, 2005a. Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Millennium Ecosystem Assessment, 2005b. Chapter 4. Biodiversity. Ecosystems and Human Well-Being: Current State and Trends, pp. 77–122 https://doi.org/10.18574/nyu/9780814760741.003.0009.

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

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial ecoregions of the world: a new map of life on earth: a new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. Bioscience 51, 933–938. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.

Ouda, S., Zohry, A.E., Noreldin, T., 2018. Crop Rotation. An Approach to Secure Future Food. Springer International Publishing, Cham https://doi.org/10.1007/978-3-030-05351-2.

Paramesh, V., Kumar, P., Parajuli, R., Francaviglia, R., Manohara, K.K., Arunachalam, V., Mayekar, T., Toraskar, S., 2023. A life cycle assessment of rice–rice and rice–cowpea cropping systems in the west coast of india. Land 12, 502. https://doi.org/10.3390/LAND12020502/S1.

Parra-Paitan, C., Verburg, P.H., 2022. Accounting for land use changes beyond the farm-level in sustainability assessments: the impact of cocoa production. Sci. Total Environ. 825, 154032. https://doi.org/10.1016/J.SCITOTENV.2022.154032.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43, 4098–4104. https://doi.org/10.1021/ES802423E/SUPPL_FILE/ES802423E_SI_003.PDF.

Piastrellini, R., Civit, B., Arena, A., 2015. Influence of agricultural practices on biotic production potential and climate regulation potential. A case study for life cycle assessment of soybean (Glycine max) in Argentina. Sustainability 7, 4386–4410. https://doi.org/10.3390/su7044386.

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

PRé Sustainability, 2022. Simapro Database Manual. Methods library, Amersfoort, Netherlands.

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

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

Semenchuk, P., Plutzar, C., Kastner, T., Matej, S., Bidoglio, G., Erb, K.-H., Essl, F., Haberl, H., Wessely, J., Krausmann, F., Dullinger, S., 2022. Relative effects of land conversion and land-use intensity on terrestrial vertebrate diversity. Nat. Commun. 13, 615. https://doi.org/10.1038/s41467-022-28245-4.

Sindelar, A.J., Schmer, M.R., Jin, V.L., Wienhold, B.J., Varvel, G.E., 2016. Crop rotation affects corn, grain sorghum, and soybean yields and nitrogen recovery. Agron. J. 108, 1592–1602. https://doi.org/10.2134/AGRONJ2016.01.0005.

Staude, I.R., Navarro, L.M., Pereira, H.M., 2020. Range size predicts the risk of local extinction from habitat loss. Glob. Ecol. Biogeogr. 29, 16–25. https://doi.org/10.1111/geb.13003.

Sustainable Agriculture Research and Education (SARE), 2020. Crop Rotation on Organic Farms (A planning manual).

The agricultural European Innovation Partnership (EIP-AGRI), 2015. EIP-AGRI Focus Group Soil Organic Matter in Mediterranean Regions.

The agricultural European Innovation Partnership (EIP-AGRI), 2016. Soil organic matter matters investing in soil quality for long-term benefits. Soil Organic Matter Matters Investing in Soil Quality for Long-Term Benefits.

The World Bank, 2018. Arable land (hectares per person) - Egypt, Arab Rep. [WWW Document]. URL https://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC?end=2018&locations=EG&start=1961&view=chart (accessed 8.2.22).

Tiemann, L.K., Grandy, A.S., Atkinson, E.E., Marin-Spiotta, E., Mcdaniel, M.D., 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecol. Lett. 18, 761–771. https://doi.org/10.1111/ele.12453.

Ukaew, S., Beck, E., Archer, D.W., Shonnard, D.R., 2015. Estimation of soil carbon change from rotation cropping of rapeseed with wheat in the hydrotreated renewable jet life cycle. Int. J. Life Cycle Assess. 20, 608–622. https://doi.org/10.1007/s11367-015-0863-1.

UN Water, 2021. Valuing water: facts and figures. Water Polit. 15–27.

UNEP-SETAC Life Cycle Initiative, 2019a. Global Guidance on Environmental Life Cycle Impact Assessment Indicators. Vol. 2.

UNEP-SETAC Life Cycle Initiative, 2019b. Global Guidance on Environmental Life Cycle Impact Assessment Indicators. Vol. 1.

UNESCO, IWSSM, U, 2019. Water Security and the Sustainable Development Goals (Series I). Series, Global Water Security Issues (GWSI).

United Nations Development Programme, Ministry of Planning and Economic Development, 2021. Egypt Human Development Report 2021 Development, a Right for all: Egypt's Pathways and Prospects (Egypt).

United Nations Economic Commission for Europe (UNECE), 2021. Life Cycle Assessment of Electricity Generation Options. United Nation, New York.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/S11367-016-1087-8.

Winter, L., Lehmann, A., Finogenova, N., Finkbeiner, M., 2017. Including biodiversity in life cycle assessment – state of the art, gaps and research needs. Environ. Impact Assess. Rev. 67, 88–100. https://doi.org/10.1016/j.eiar.2017.08.006.

World Food Programme, 2022. Egypt. [WWW Document]. URL https://www.wfp.org/countries/egypt (accessed 9.11.22).

Xiong, J., 2017. NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-Support Analysis Data (GFSAD) Cropland Extent 2015 Africa 30 M V001 [Data Set] [WWW Document]. NASA EOSDIS L. Process. DAAC. https://doi.org/10.5067/MEaSUREs/GFSAD/GFSAD30AFCE.001.

Xu, Z., Chen, X., Liu, J., Zhang, Y., Chau, S., Bhattarai, N., Wang, Y., Li, Yingjie, Connor, T., Li, Yunkai, 2020. Impacts of irrigated agriculture on food–energy–water–CO2 nexus across metacoupled systems. Nat. Commun. 11, 5837. https://doi.org/10.1038/s41467-020-19520-3.

Zhang, L., Yuan, J., Zhang, M., Zhang, Y., Wang, L., Li, J., 2022. Long term effects of crop rotation and fertilization on crop yield stability in southeast China. Sci. Rep. 12, 14234. https://doi.org/10.1038/s41598-022-17675-1.

Zhao, J., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P., Zeng, Z., Olesen, J.E., Zang, H., 2022. Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. Nat. Commun. 131 (13), 1–9. https://doi.org/10.1038/s41467-022-32464-0 2022.

Ziadat, F.M., Zdruli, P., Christiansen, S., Caon, L., Monem, M.A., Fetsi, T., 2021. An overview of land degradation and sustainable land management in the near East and North Africa. Sustain. Agric. Res. 11, 11. https://doi.org/10.5539/sar.v11n1p11.