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Research article

Regeneration costs of topsoil fertility: An exergy indicator of agricultural impacts

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A R T I C L E I N F O

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A B S T R A C T

In recent years, heightened environmental concerns linked to agriculture have surged, with soil degradation standing out as a global issue. However, prevailing sustainability assessment methodologies in agriculture often overlook soil systems due to their intricate nature. This study aims to develop a methodology for evaluating soil degradation in agricultural practices using exergy regeneration costs. These costs determine the exergy required to restore soil fertility to pre-harvest levels. The methodology covers key soil factors like nutrients, organic matter, and prevalent issues like salinity, acidification, and erosion. For each of these factors, exergy regeneration costs are determined based on the energy needed to execute an optimal process for reverting the soil to its original or ideal state. The methodology has been applied to data from agricultural trials, showing that the calculated soil replacement cost is significantly higher compared to one of the most energy-demanding processes in agriculture, the use of urea. This demonstrates that agricultural soil degradation needs to be quantified for a correct evaluation of agricultural practices and their sustainability.

1. Introduction

Around 11,500 years ago, humans started cultivating their own vegetables, and since then, fertile soils have represented one of the most valuable resources on the planet. However, the overexploitation of fertile soils, triggered by intensive agriculture systems, has resulted in a degradation rate that is much faster than the natural regenerative capacity of soils. In this context, fertile soils can be easily compared to fossil fuels: we are "combusting" them much faster than their regeneration capacity.

In recent decades, crop production yields have increased through intensive techniques that have led to various environmental impacts, soil quality degradation, and erosion. In Europe, it is estimated that 12 million hectares are affected by erosion, which generates losses of 1250 million euros per year (Görlach et al., 2004). The escalating global demand for agricultural output, driven by an increasing population, necessitates a concerted effort to enhance productivity while mitigating environmental impact. Within this context, agroecological practices have emerged as a compelling solution to attain requisite agricultural production levels without jeopardizing ecological integrity (Pörtner et al., 2022). Agroecological practices promote sustainable agriculture by incorporating methods such as agroforestry, intercropping, biodiversity enhancement, organic amendments, livestock integration, cover crops, and reducing adverse health and environmental impacts (Bezner Kerr et al., 2021; FAO, 2023; Tataridas et al., 2022). Specifically, in the study of Bezner Kerr et al. (2021), it has been observed that 78 % of the reviewed articles on agroecological practices show positive results in terms of food security and nutrition based on improvements in soil degradation, water pollution, greenhouse gas emissions, and depletion of non-renewable resources, among others.

Environmental impact assessment methodologies, such as the Product Environmental Footprint (PEF), use Life Cycle Assessment (LCA) to quantify the environmental impacts of products based on international standards. The PEF method, when applied to farming systems, measures environmental impacts throughout a product's life cycle and optimizes fertiliser use but fails to assess how inputs affect soil organic matter,

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nutrients, compaction, and erosion. It also overlooks the specific needs of different soils and crops, treating the soil as a "black box" and focusing only on inputs and outputs. This evidence indicates that environmental assessments of agricultural practices have not included soil health or soil fertility as a parameter to be considered (van der Werf et al., 2020).

This is to the detriment of agroecological practices when compared to intensive agriculture, where soil is often degraded in favour of production. The intricacy arising from the interplay of physical, chemical, and biological parameters within the soil poses a challenge to its comprehensive assessment. A primary and significant limitation encountered in the examination of soil systems pertains to the inability to rely on a singular indicator for the characterization and evaluation of soil (Bongiorno et al., 2019; Bünemann et al., 2018; Dexter, 2004; Johannes et al., 2019). Considering the intricate composition of soil systems and the multitude of interacting factors and parameters, some investigations have aimed at delineating a "minimum data set" (MDS) of soil characteristics deemed most pivotal in influencing quality (Garrigues et al., 2012; Hughes et al., 2023; Reynolds et al., 2008, 2009; Thoumazeau et al., 2019; Xu et al., 2017).

The magnitude and importance of soils are not only reflected in the complex set of indicators that need to be assessed but also in the discussion surrounding the definition of the terms under assessment. The Food and Agriculture Organization of the United Nations (FAO) defines soil fertility as "the capacity of the soil to support the growth of plants on a sustained basis yielding quantities of expected products that are close to the known potential" (Gachene and Kimaru, 2003). Soil Science Society of America defines soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity" (Karlen et al., 1997). Soil health is considered equivalent to soil quality by some authors (Bünemann et al., 2018). However, soil health is positioning itself as the appropriate term to talk about all the ecosystem services that soil provides (Hou et al., 2020). Without engaging in this discussion, soil fertility or soil degradation are the terms assessed by this study as our target system is agricultural soils and our initial focus is mainly on the value of these soils due to their productive capacity.

Thus, our aim is to propose for the first time exergy as a unifying indicator to evaluate the overall effects of agricultural practices, including the effects on soil degradation, which are neglected by environmental assessment tools. In this work, the most important tools to quantify the degradation or improvement of soil by agricultural processes will be developed and evaluated using real field data. To start with, the basis of exergoecology and why it is proposed as a theory for assessing soil fertility will be clarified.

2. Methodology

2.1. Previous foundation: exergy role in soil quality evaluation

Exergy is a thermodynamic property that measures the maximum useful work that can be extracted from a system as it comes into equilibrium with its surroundings. Unlike energy, which represents the total capacity to do work, exergy takes into account the quality of the energy.

In any exergy evaluation, it is necessary first to define a reference state. Thanatia represents a planet where all the resources have been dispersed throughout the Earth's crust, a planet of total degradation. The upper continental crust represents the starting point for evaluating the exergy of the mineral capital on Earth because it provides the concentration of the 300 most abundant elements (Valero et al., 2011). This approach is the basis of exergoecology, the theory that assesses the degradation of natural capital using exergy analysis. The consumption of natural resources implies the destruction of organized systems and dispersion, thus creating entropy or exergy destruction (Valero et al., 2014).

As has been done for the mineral capital, exergy can be a tool to assess soil quality as the highest useful working capacity of the soil to produce a crop while maintaining its conditions. Soil has typically been a forgotten part of the environmental assessment of agriculture impacts. The degradation of soil fertility threatens the sustainability of the planet and if this path continues, Earth could eventually turn into Thanatia.

However, the Thanatia model is insufficient for an exergy evaluation of soil fertility since it does not consider the specific attributes. The first approach was to include the attributes of agronomic soil as a part of Thanatia (Valero et al., 2019), then we realized that it is more appropriate to establish an optimum soil "OptSOIL" as a reference and we named it Pristinia.

The methodology developed in previous papers included the study of soil parameters and emphasized the necessity of incorporating inorganic, organic, and biological fractions to effectively represent soil in a straightforward yet robust manner. The inorganic part of the soil includes texture and nutrient exergy calculation by means of their concentration and chemical exergy (Valero et al., 2020). The organic matter and microorganisms were assessed considering their chemical exergy and eco-exergy (Valero et al., 2021).

The optimal levels of the inorganic and organic parts together conform Pristinia, defined as the "OptSOIL" or Pristine state, an ideal fertile planetary crust copiously fertile (Valero et al., 2022). Given the global diversity of soil types, the establishment of optimum levels for the parameters that define Pristinia is intended solely as a reference for exergy calculation, not as a guide for agricultural practices; the goal is to create a theoretical framework that assesses soil quality and fertility, enabling the comparison of any soil's degradation degree relative to the optimal state. The optimal agronomic values of Pristinia have been established according to numerous bibliographic references and assumptions (Valero et al., 2022). Thus, any real agricultural soil will be an intermediate soil between Pristinia and Thanatia. In this way, a complete exergy methodology that quantifies soil quality and fertility has been obtained. This methodology has proven effective in evaluating soil degradation due to the erosion process (Palacino et al., 2022).

The next step, and the main objective of this article, is to establish a regeneration value for soil fertility loss due to agricultural practices. In other words, the aim is to quantify the cost involved in restoring soil fertility that has been degraded or lost due to agricultural activities. It is often argued that soil fertility is a natural benefit provided by nature at no cost. However, when this fertility is lost, it incurs a cost that is not always explicitly acknowledged in economic terms. Thus, the concept of exergy is proposed to calculate the regeneration cost as a tool for this purpose. Exergy is a measure of the energy available to perform useful work in a system, and in this context, it will be used to estimate the energy required to restore lost soil fertility.

In this context, exergy is used in this work to calculate the energy embodied in a theoretical remediation and regeneration process that could potentially restore the impacts suffered by fertile soils.

2.2. Quantifying soil degradation from agricultural processes through exergy regeneration costs

The exergy replacement cost of a mine is defined as the exergy required by a given available technology to restore the deposit from the dispersed state of Thanatia (all minerals are dispersed throughout the crust), to the physical and chemical conditions in which it was first delivered by the ecosystem (Valero, 1998; Valero et al., 2013, 2014).

Conventional Life Cycle Assessments (LCA) analyze a product or process from cradle to gate or, in some cases, to grave. In contrast, exergy replacement costs enable a more comprehensive analysis by incorporating an additional stage: the trajectory from grave to cradle, thereby closing the material cycle (cradle-grave-cradle). This trajectory involves quantifying the exergy costs required to replace the extracted compounds using currently available technologies, transitioning from the dispersed state of Thanatia to the conditions present in the environment (Valero et al., 2014).

Similar to mines, soil is a resource that acts as a crop development system and a reservoir of nutrients for plants and microorganisms. Thus, in soil the exergy replacement costs represent the exergy required, considering the irreversibility of the different processes, to incorporate and replenish the soil from a degraded state to a state where the soil is more fertile. Therefore, the term "exergy regeneration cost" is used in soil.

In the case of the soil system in the agricultural process, the grave is considered to be the state of the soil after the agricultural process (final state). The cradle can refer to either the initial state of the soil before the agricultural process or the "OptSOIL". In the first case, the replacement analysis examines the differences between the soil before and after agricultural processes and estimates the exergy costs necessary to restore the initial conditions (Fig. 1). In addition to calculating the exergy regeneration costs from the final soil state to the initial state, it is also possible to calculate the exergy regeneration costs needed to achieve an optimal condition defined by the Pristine state, "OptSOIL".

Regeneration costs in the grave-to-cradle approach, shown in Fig. 2, are used to estimate the loss of soil fertility resulting from agricultural production through energy units. The regeneration processes consider four key factors: nutrients, organic matter, salinity/sodicity, and acidification.

Fig. 1. Schematic representation of Pristinia and Thanatia.

2.2.1. *Nutrient amendment*

Plant growth results from the extraction of nutrients from the soil. Without a fertilisation process, the concentration of nutrients in the soil can decrease and crop growth problems may occur. Nitrogen, phosphorus, potassium, calcium, and magnesium are needed in high concentrations and are known as macronutrients. Copper, iron, manganese, and zinc are considered among all the micronutrients. These nutrients were already selected in previous work due to the greater availability of data in conventional soil analyses (Valero et al., 2022).

The regeneration of soil nutrients can be done by means of mineral, organic or biological fertilisers and organic amendment, and has an associated cost that corresponds to the energy needed to produce these fertilisers together with the energy needed for their transportation and distribution to the field. In this methodology, the costs associated with a decrease in the level of nutrients are formulated as the energy needed in the production process of each nutrient in its inorganic form. For this purpose, a detailed literature review was conducted, comparing and analysing different data sources, ultimately selecting the most representative value for each nutrient.

Urea and ammonium nitrate are the most commonly used nitrogen compounds. In both cases, the main raw materials needed are ammonia and natural gas (Yara, 2018). In both cases, most of the energy needed for their production is due to the high energy demand of ammonia production. Ammonia synthesis is an energy-intensive process because it involves the combination of nitrogen from air and hydrogen (from natural gas), which requires high pressure and temperature conditions (Kirova-Yordanova, 2017).

The values of energy consumed per unit N found in the literature range from 40 to 78.23 MJ (Amenumey and Capel, 2014; Dachraoui and Sombrero, 2020; Erdal et al., 2007; Kaab et al., 2019; Khaledian et al., 2010; Mohammadi and Omid, 2010; Mostashari-Rad et al., 2019; Šarauskisa et al., 2019; Tian et al., 2019; Aguilera et al., 2015). Furthermore, Ecoinvent v3.8 is considered as a data source, specifying the process energy, indirect energy costs, and transportation and packaging. Based on all these sources and data, an average value of 67.8 MJ/kg N is established as the energy required for obtaining urea, including packaging and transportation (Table 1).

Based on the latest 2022 data from Yara (2022), while the majority of nitrogen fertiliser plants rely on natural gas, other hydrocarbons or coal may also be utilized. Notably, coal is the predominant choice in most plants in China. Energy consumption can vary significantly across different plants. In an efficiently operated plant using natural gas, approximately 42 GJ/t N is needed. Converting nitrogen into ammonia requires about 51 GJ per ton. Additionally, as a general guideline, ammonia plants utilizing coal typically demand 50%–100% more energy per unit of nitrogen produced. It is important to note that this calculation excludes packaging and transportation costs, which are factored into the 67.8 MJ/kg N value selected in this study. Therefore, the established value would realistically represent the energy required for urea production.

In the case of phosphorus, phosphate fertilisers are generally produced by adding acid to phosphate rock. If phosphoric acid is used, a single phosphate is produced with a P_2O_5 content between 16 and 21%. If phosphoric acid is used, triple phosphate is produced with a P_2O_5 content between 43 and 48% (World bank group, 1998). According to different literature sources, the energy required to produce phosphate fertilisers ranges from 12 to 17.5 MJ/kg $P_2O_{5,}$ with the average value being 14.4 (Amenumey and Capel, 2014; Dachraoui and Sombrero, 2020; Erdal et al., 2007; Kaab et al., 2019; Khaledian et al., 2010; Mohammadi et al., 2010; Mostashari-Rad et al., 2019; Šarauskisa et al., 2019; Tian et al., 2019; Aguilera et al., 2015). The main reason that can be attributed to the low values obtained for the phosphate fertilisers in the different literature references is that they could be considering a mixture of organic and inorganic fertilisers. On the other hand, there is another value for triple phosphate in literature obtained by Kirova-Yordanova (1998) and Kirova-Yordanova (2017) of 59.3 MJ.

This study has focused on inorganic compounds containing only phosphorus, so the average value between the Ecoinvent data source and the one provided by Kirova-Yordanova (1998), which corresponds to 49.08 MJ/kg P_2O_5, was considered.

In addition, more detailed and updated data for phosphorus, similar to those available for nitrogen, have been identified. These values are based on real-world data (Aguilera et al., 2015; Ramírez and Worrell, 2006) and account for the energy consumed in the production of each fertilizer, as well as the indirect energy used, such as the extraction of phosphorus from mines.

Considering the different figures from the sources and databases cited above, an average of 50.9 MJ/kg P has been adopted as the representative value for the exergy evaluation of phosphorus compounds (Table 1).

In the case of potassium, the most commonly used form of fertilizer is potassium chloride (90%) (Marschner, 2011). To a lesser extent, other products such as potassium sulfate, potassium nitrate, and magnesium-potassium salts may also be used. The values assigned to the energy consumed for potassium fertilisers in the references analysed range from 4.22 to 13.8 MJ/kg K_2O, with the average value being 10.06 MJ/kg (Amenumey and Capel, 2014; Dachraoui and Sombrero, 2020; Erdal et al., 2007; Kaab et al., 2019; Khaledian et al., 2010; Mohammadi et al., 2010; Mostashari-Rad et al., 2019; Šarauskisa et al., 2019; Tian et al., 2019). Similar to nitrogen, more detailed and updated data for potassium have been obtained from real-world sources (Aguilera et al., 2015; Ramírez and Worrell, 2006). Considering the different figures from these sources, an average of 15.1 MJ/kg K has been adopted for the exergy evaluation of potassium compounds (Table 1).

For the remaining nutrients (copper, iron, manganese, zinc, magnesium, and calcium), available bibliographic references are limited. This is primarily because the quantities of these nutrients used are significantly lower than those of nitrogen, phosphorus, and potassium.

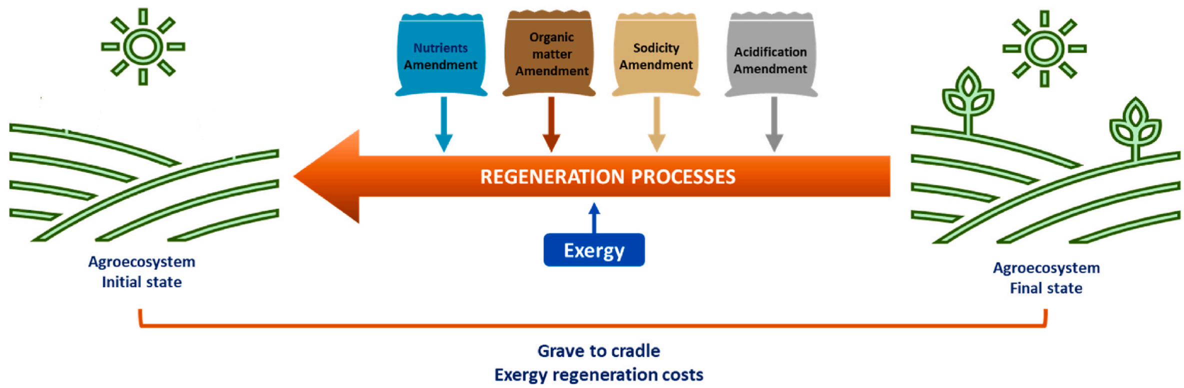

Fig. 2. Regeneration processes considered in the grave to cradle exergy assessment.

Table 1
Data of exergy costs for each type of nutrient applied to the soil.

Nutrient	Exergy value	Units	Source
Inorganic nitrogen	67.8	MJ/kg N	(Aguilera et al., 2015; Ramírez and Worrell, 2006; Ecoinvent v3.8; Kirova-Yordanova, 2017)
Phosphorus	50.87	MJ/kg P	(Aguilera et al., 2015; Ramírez and Worrell, 2006; Kirova-Yordanova, 1998; Ecoinvent v 3.8)
Potassium	15.06	MJ/kg K	(Aguilera et al., 2015; Ramírez and Worrell, 2006)
Calcium	22.89	MJ/kg Ca	Ecoinvent v3.8
Magnesium	31.2	MJ/kg Mg	Ecoinvent v3.8
Copper	222.94	MJ/kg Cu	Ecoinvent v3.8
Iron	9.25	MJ/kg Fe	Ecoinvent v3.8
Manganese	73.08	MJ/kg Mn	Ecoinvent v3.8
Zinc	28.77	MJ/kg Zn	Ecoinvent v3.8

According to FAO (Roy et al., 2006), sulphates and oxides are the most commonly used forms in the production of fertilisers containing other nutrients, although other types of complexes or chelates of some metals can also be found, as well as borates and carbonates in the case of Ca. For reasons of data unavailability, the selected values have been simplified to those provided for these compounds by the Ecoinvent v3.8 database. Thus, the exergy cost per kg nutrient required for copper, iron, manganese, zinc, magnesium, and calcium is 222.9 MJ, 9.25 MJ, 73.1 MJ, 28.8 MJ, 31.2 MJ and 22.9 MJ, respectively (Table 1).

The content of the different nutrients provided by the soil analyses will reveal differences between the soil in the state after the agricultural process and the selected replacement level (initial soil state or optimum soil defined as "OptSOIL"). It should be noted that in some cases, certain nutrients may maintain or even increase their content, meaning they will not require restocking. Consequently, the amendment for these nutrients will be zero, as will their contribution to the overall regeneration costs of the soil.

The following equation (Eq. (1)) should be used for the calculation of nutrient content needed for the quantity of amendment. Equation (2) should be applied to estimate the Nutrient Amendment (MJ/ha) based on the result of equation (1) and the fertiliser production cost (exergy, Table 1).

$$Nutrient\left(kg/_{ha}\right) = Variation\ content\left(kg\ Nutrient/_{kgsoil}\right)\cdot 10\,000\,\frac{m^2}{ha}\cdot 0.3m\cdot 1400\,kgsoil/_{m^3} \quad (1)$$

$$Nutrient\ Amendment\ (MJ/ha) = Nutrient\left(\frac{kg\ Nut}{ha}\right)\cdot Fertilizer\ prod.\ Cost\left(\frac{MJ}{kg\ Nut}\right) \quad (2)$$

2.2.2. Organic matter amendment

Organic matter is of great relevance in soil due to the influence it has on a large number of soil properties, both physical, chemical and biological (Lal, 2016). Organic matter can generate modifications and alterations in soil structure, nutrient reservoir, cation exchange, pH, or the activity of microorganisms and nutrient cycles, among other properties (Arshad and Martin, 2002; Johnston, 1991; Jurandy et al., 2013; Murphy, 2014; Panagos et al., 2020; Weil and Brady, 2017). Moreover, the stability of organic matter in soils is directly related to its carbon storage capacity, preventing CO_2 emissions (Lal, 2016). In fact, the stabilisation of organic matter in soils is a topic that has been studied in depth because the large amount of organic matter in soils represents one of the largest reservoirs of organic carbon in the world (Arshad and Martin, 2002; Bongiorno et al., 2019; Dexter et al., 2008; Johnston, 1991; Jurandy et al., 2013; Kemper and Koch, 1966; Krull et al., 2004; Minasny and McBratney, 2018). Thus, the content of organic matter in the soil is of great importance.

Increasing crop production and yields lead to soil organic matter losses, often occurring rapidly in the first years after cultivation. In addition, further losses can occur through drainage and land use change over the years, typically in the range of the first 5–40 years (Lal, 2017).

An estimation of the regeneration costs of incorporating the necessary amount of organic matter into the soil system will be carried out to better understand the amendment processes and gain insight into their importance and value. As for nutrients, the replenishment of organic

Table 2
Exergy cost of organic matter amendment.

	Exergy cost (MJ/kg)	Conversion factor
Compost	0.076	10%

matter in the system will be studied based on the regeneration costs.

To estimate the energy involved in incorporating organic matter in the field, it is necessary to determine the energy and exergy of the processes involved in soil incorporation. By-products and wastes like manure, slurry, or biomass, among others, represent one of the main sources of organic matter that is applied to soils. It can be applied directly or after a stabilisation process as composting. Compost is selected as representative of the replenishment of organic matter.

In the literature, not much detail has been found on the energy involved in incorporating organic matter into the soil. In studies such as those by Erdal et al. (2007), Mohammadi et al. (2010), and Mohammadi and Omid (2010), very rough values of 303.1 MJ/kg and 300 MJ/kg are used without providing details on the processes or methods used to obtain these figures.

Windrow composting, where long rows of organic matter are piled, is the most representative method. According to the Ecoinvent database, the energy needed for this process is low (0.076 MJ/kg) and is mainly due to the machinery needed to turn over the piles. However, in this case, transport is not considered as it is typically minimal due to the fertilizers being applied close to the point of production (Table 2).

No other treatment or production methods are being considered for the organic matter because, in most cases, it comes from waste or by-products. Nevertheless, the incorporation of organic matter into the soil, such as compost, manure, or the form in which the amendment is made, does not result in an immediate increase in organic matter. Instead, it requires a period of time for the added organic matter to become integrated into the soil's organic matter. Organic matter applied to soil undergoes decomposition processes, and only a fraction is stabilised in the long term. However, this mechanism is not yet known in detail due to the multiple factors affecting carbon stabilisation in soils. The biodegradability of soil organic matter is associated with the composition of the organic matter itself, properties of the soil matrix (such as pH, O_2 content, clay content, and mineralogy), microbial characteristics, and climatic aspects such as temperature and humidity (Cookson et al., 2005). According to Lützow (Lützow et al., 2006), about two-thirds of the organic matter applied to soils decomposes in approximately 1–2 years, with subsequent slower decomposition leading to a total loss of about 90% between 10 and 100 years. This aligns with the linear relationship obtained by Kong et al. (2005) in ten Mediterranean cropping systems where a soil organic carbon (SOC) conversion of 7.6 % over ten years was obtained.

Thus, a soil incorporation factor has been included in addition to the exergetic cost applied to the compost production selected. This factor is defined as the percentage of organic matter applied to the soil that decomposes and is recalcitrant to form part of the soil organic matter. Considering the studies of Lützow et al. (2006), the selected soil incorporation factor is 10%, i.e. it is necessary to make an amendment 100 times higher than necessary in order to recover all the organic matter lost from the soil due to agricultural cultivation processes (Table 2).

Equation (3) is defined for calculating the organic matter content needed for the quantity of amendment. Equation (4) is applied to estimate the organic matter amendment (MJ/ha) based on the result of equation (3) and the compost exergy cost considering a value of 10% assimilation rate of organic matter in the soil (Table 2).

Table 3
Exergy and sulphur content of gypsum.

Gypsum	Exergy	3.7	MJ/kg S

$$OM\left(\frac{kg}{ha}\right) = \frac{\%\ Variation}{100}\left(\frac{kg}{kgsoil}\right)\cdot 42\,000\,000\,\frac{kg\ soil}{ha} \tag{3}$$

$$Organic\ Matter\ Amendment(MJ/ha) = \frac{OM\left(\frac{kg}{ha}\right)\cdot\left[Compost\left(\frac{kJ}{kg}\right)\right]}{1000\,\frac{kJ}{MJ}} \tag{4}$$

2.2.3. Sodicity

The exergy cost for gypsum has been established as a sodified soil remediator (Table 3). One of the most commonly used methods to remediate sodified soils is the addition of gypsum ($CaSO_4{\cdot}2H_2O$), which allows the exchange of Na^+ for Ca^{2+} and decreases sodicity. Sodicity is one of the main causes of soil fertility loss. It mainly affects irrigated soils, the extent of which has increased dramatically over the last 50 years. Irrigation water contains salts that accumulate in the soil. This effect is even more pronounced in arid regions due, on the one hand, to the higher concentration of salts in the water and, on the other hand, to the higher amount of water needed. In addition, fertilisers also contribute to increased salt concentration in the soil (Weil and Brady, 2017).

Sodium is a harmful element to the soil, which affects its physical properties by causing the collapse of aggregates, resulting in soil compaction, loss of water infiltration and severe limitations in the vertical conduction of gases (Hazelton and Murphy, 2017; Hillel, 2004; Lal, 2017; Murphy, 2014; Weil and Brady, 2017). If the sodium proportion is high, the soil is defined as sodic (EPS: Exchangeable Proportion of Sodium >15). In this case, plant growth is hindered. The growth of sensitive plants is affected when the EPS is around 5 (Hazelton and Murphy, 2017; Hillel, 2004; Lal, 2017; Murphy, 2014; Weil and Brady, 2017). Equation (5) is used to calculate the sulphur content needed for the quantity of amendment based on the EPS and the Carbon Exchange Capacity (CEC). Due to the impurities in the gypsum and the inefficiency of the process in general, these quantities are adjusted with an extra 30 % gypsum to account for the incomplete reactivity (Weil and Brady, 2017). The conversion from centimol of charge to grams of gypsum, the conversion from gypsum to sulphur, including the need for extra 30 % and the conversion to hectares is represented by the factor 873.6. Equation (6) is applied to estimate the sodicity amendment (MJ/ha) based on the result of equation (5) and gypsum production exergy cost (Table 3). Considering the average of the primary energy required to extract the gypsum and the primary energy required to obtain the gypsum from flue gas desulphurisation as S (Williams et al. (2010)).

$$Sulphur\left(\frac{kg}{ha}\right) = \left(\frac{EPS_{final} - EPS_{initial}}{100}\right)\cdot CEC\cdot 873.6 \tag{5}$$

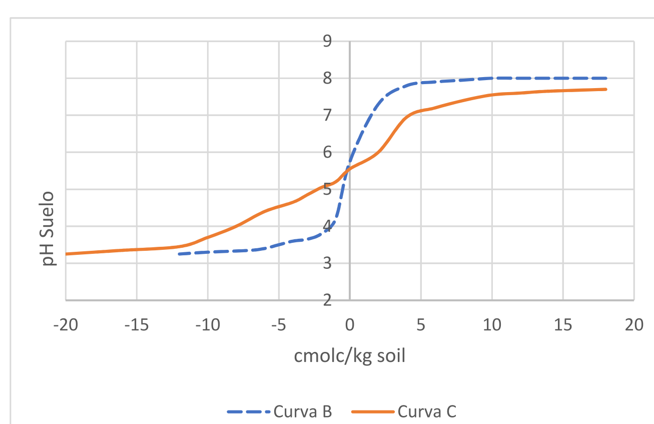

Fig. 3. Buffering of soil pH. Curve B, is for soils with lower clay and organic matter content. Curve C, is for soils with higher organic matter and clay content. Adapted from Weil and Brady (2017).

$$Sodicity\ Amendment\left(\frac{MJ}{ha}\right)=Sulphur\left(\frac{kg}{ha}\right)\cdot Gypsum\ prod.\ cost\left(\frac{MJ}{kg\ S}\right) \tag{6}$$

2.2.4. Acidification

Plant residue removal by agriculture and forestry exports plant ash from managed ecosystems, while the use of ammonia-based fertilisers, imported to replace nutrients lost by harvest, dramatically accelerates soil acidification (Hazelton and Murphy, 2017; Marschner, 2011; Panagos et al., 2020; Weil and Brady, 2017).

Soil acidification affects a wide range of properties, from the capacity of plant roots to take up nutrients to the activity of soil microorganisms. To decrease soil acidity, the most common solution is to amend the soil with alkaline materials, referred to as agricultural limes (Marschner, 2011; Weil and Brady, 2017). Following an approximation obtained by Weil and Brady (2017) for different types of soils, values of the amount of ground limestone needed to raise the pH to 6.5 are obtained.

Fig. 3 shows the buffering of soils against pH changes when acid (H_2SO_4) or base ($CaCO_3$) is added. A well-buffered soil (C) and a moderately buffered soil (B). The well-buffered soil (C) has a higher organic matter content and/or more highly loaded clay than the moderately buffered soil (B).

The difference between the soil pH and the desired pH is extrapolated onto the corresponding curve for the soil under study, allowing for the estimation of the amount of $cmol_c$ limestone per kilogram of soil required to achieve the desired pH change. Subsequently, the exergy cost for limestone has been determined based on its calcium content (Table 4), taking into account the average primary energy required for limestone extraction as Ca (Williams et al., 2010). Therefore, once the soil has been analysed and the amount of limestone required is known, the equivalent amount of calcium per hectare is calculated (Eq. (7)) considering a soil depth of 0.3 m and a soil average density of 1400 kg/m^3. Then, the cost is applied directly to the calculated amount (Eq. (8)).

$$Ca\left(\frac{kg}{ha}\right)=CaCO_3\left(\frac{g}{kg}soil\right)\cdot\frac{\frac{39g}{mol}}{\frac{100g}{mol}}\cdot\frac{1g}{1000kg}\cdot\left.10000\frac{m^2}{ha}\cdot 0.3\,m\cdot 1400\,kg\,soil/_{m^3}\right) \tag{7}$$

$$Acidification\ Amendment\left(\frac{MJ}{ha}\right)=Ca\left(\frac{kg}{ha}\right)\cdot Fertilizer\ prod.\ cost\left(\frac{MJ}{kg\ Ca}\right)$$

3. Results

In this section the exergy regeneration cost methodology is validated with real results from field trials. As the aim is to see the influence of the cultivation process when comparing two different fertilisation treatments, the initial state considered is the state of the soil before the cultivation process.

Field tests have been conducted during one campaign for two different crops (wheat and triticale) at the same location, Gea de Albarracín (Spain). The field tests for wheat and triticale crops were conducted under two different fertilisation scenarios: Treatment 1, basal fertilisation with NPK (0-30-0) at 95 kg/ha and topdressing with regular Urea at 150 kg/ha; Treatment 2, basal fertilisation with NPK (0-15-0) at 187.5 kg/ha and topdressing with coated urea at 150 kg/ha. The difference between the two treatments is the composition of the NPK fertiliser for basal fertilisation and the use of coated urea in the topdressing fertiliser. In NPK, the phosphorus percentage differs, and the dosage varies to determine which approach is more effective: higher dosage or lower but more concentrated dosage. In the case of the treatment with coated urea, it will result in a slower dosage and release of nitrogen in the soil.

Table 4
The exergy regeneration cost of limestone is the amount of calcium content in the fertilisers.

Limestone	Exergy cost	2.3	MJ/kg Ca
	Content	0.39	kg Ca/kg compound

In each treatment, crop yields were 3.75 t crop/ha and 6.62 t crop/ha for triticale, for treatment 1 and treatment 2, respectively. In the case of wheat, the yields were 8.27 t crop/ha for treatment 1 and 6.47 t crop/ha for treatment 2.

Soil analyses were conducted at the beginning of the field test and at the end of the crop harvest (Table 1). The parameters were evaluated to see whether they had been influenced positively or negatively after the agricultural process.

The regeneration is evaluated by comparing the initial and final states, aiming to restore soil fertility and quality to the levels before crop cultivation.

As shown in Table 5 treatment 1 experiences significant degradation in essential soil nutrients, such as potassium, calcium, magnesium, copper, and manganese, in the case of triticale. On the other hand, treatment 2 shows degradation in phosphorus, copper, and iron. These degradations indicate a loss of nutrients in the soil, which is a concern as these nutrients are crucial for the healthy growth of crops.

In terms of regeneration effort (Fig. 4) it is observed that treatment 1 requires substantially more effort (1.07 toe/ha) to restore nutrient levels to the initial soil conditions compared to treatment 2 (0.16 toe/ha). This regeneration effort involves the application of additional practices or inputs to correct soil degradation and restore its fertility.

In the case of wheat, the results indicate that treatment 1 experiences degradation and nutrient loss in various aspects, including organic matter, phosphorus, iron, and zinc. On the other hand, treatment 2 shows a decrease, especially in organic matter, phosphorus, and zinc. Although treatment 2 has fewer parameters showing a decrease, the required regeneration effort is slightly higher (1.20 toe/ha) compared to treatment 1 (1.02 toe/ha), mainly due to the greater loss of organic matter.

The loss of organic matter in the case of wheat for treatments 1 and 2 ranges approximately between 6 and 8%. This loss constitutes the primary contributor to regeneration costs, even though the loss of P in both treatments is higher than that in the case of triticale in treatment 2. This observation underscores the significance of organic matter throughout the soil system, as it plays a role in physical, chemical, and biological properties, as well as interacting in the biogeochemical cycles of the soil. Hence, the loss of organic matter in the soil has a substantial impact and entails a significant cost for its recovery, not only in effort but also in time. In the case of triticale, no decrease in organic matter is observed and the regeneration cost is due to the loss of nutrients.

In addition, it is observed that micronutrients can experience losses greater than macronutrients; however, their regeneration costs are lower, as seen in the case of iron or zinc in wheat. Another example is observed in the case of triticale, the loss of 28% phosphorus in the case of treatment 2 accounts for 93% of regeneration costs, whereas a loss of 39% iron contributes to regeneration costs by approximately 5%. These lower costs stem from the fact that, even though the difference between initial and final soil levels may be greater, the concentrations are smaller.

In these field trials, there is no cost associated with the remediation of sodification and acidification. The problems in this area are related to the loss of organic matter, nutrients, and basicity. However, sodification and acidification are relevant problems in other cases.

If these data are compared per unit of crop obtained, in the case of triticale, the values are 0.28 toe/t crop and 0.02 toe/t crop for treatment 1 and treatment 2, respectively. In this case, the difference in regeneration costs needed for each treatment is 0.26 toe/t crop, compared to the observed difference of 0.90 toe/ha between treatment 1 (higher

Table 5
Key parameters comparing soils of wheat and triticale before and after.

	Unit	INITIAL TRITICALE	TRITICALE (treatment 1)	TRITICALE (treatment 2)	INITIAL WHEAT	WHEAT (treatment 1)	WHEAT (treatment 2)
pH	-	8.15	8.18	8.28	8.00	8.32	8.33
Organic matter	%	2.26	2.32	2.44	4.20	3.96	3.86
Total Nitrogen	%	0.14	0.16	0.16	0.25	0.25	0.24
N organic	g/100g	0.11	0.11	0.11	0.20	0.19	0.18
N inorganic	mg/kg	370.06	531.92	455.64	480.20	608.24	604.34
C/N	-	9.20	8.33	8.83	9.90	9.34	9.27
P	mg/kg	104.30	108.93	75.50	98.70	44.71	66.50
K	mg/kg	421.60	374.43	522.03	485.20	604.47	628.17
Ca	mg/kg	3033.00	2658.33	3080.33	4401.00	4401.52	5225.74
Mg	mg/kg	107.20	92.93	128.63	240.40	287.26	277.34
Na	meq/100g	1.23	0.41	0.76	0.94	0.92	0.51
CEC	meq/100g	18.30	15.40	18.50	26.10	26.79	30.48
Cu	mg/kg	0.70	0.57	0.60	2.80	3.03	3.91
Fe	mg/kg	21.50	30.60	13.13	14.20	8.22	17.12
Mn	mg/kg	10.40	5.57	24.93	4.30	19.38	11.85
Zn	mg/kg	1.20	1.43	1.63	3.40	2.43	3.16
Sand	%	65.40	71.47	58.23	50.90	54.20	60.20
Silt	%	17.60	15.53	22.07	27.20	20.30	20.97
Clay	%	17.00	13.00	19.70	21.90	25.50	18.83
EPS (sodicity)	%	6.72	2.66	4.11	3.60	3.43	1.67

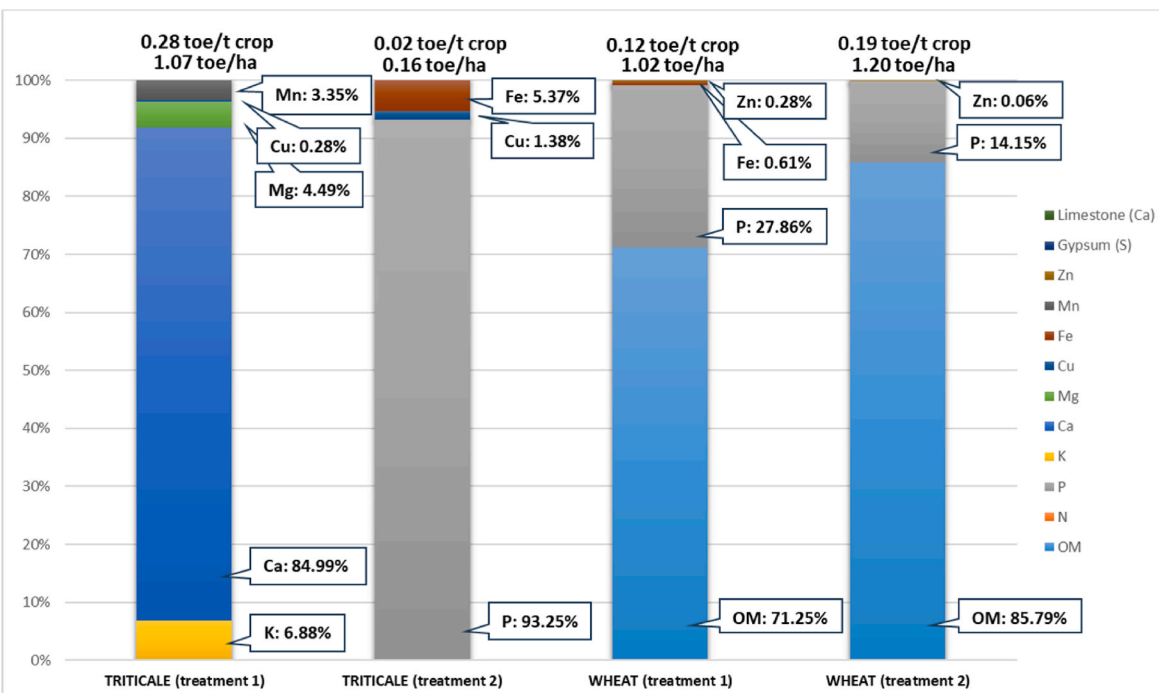

Fig. 4. Contribution of each nutrient to the regeneration exergy costs.

remediation) and treatment 2 (showing less nutrient degradation) (Fig. 4).

In the case of wheat, when considering crop production, regeneration costs for treatment 1 and treatment 2 are 0.12 toe/t crop and 0.19 toe/t crop, respectively. In this scenario, treatment 2 shows a greater decrease in soil nutrients. However, when considering regeneration costs per ton of wheat obtained, the difference shifts from 0.18 toe/ha between treatments to 0.06 toe/t crop. It is observed that the difference between both regenerations (per hectare or ton of crop) is similar, as the yield in both treatments is comparable, with a slightly higher yield in the case of treatment 1.

4. Discussion

In both crops, it is observed that treatments with lower crop production show a greater need for remediation. The decline in nutrient concentration could be due to plants' lack of nutrient uptake during growth, either due to adverse soil conditions, deficiencies in fertilisation, or limitations in water availability. Additionally, other processes, such as leaching or the decomposition of organic matter, can affect the nutrient composition in the soil. It is important to note that the relationship between crop production and nutrient concentration in the soil is complex and can vary depending on the specific soil conditions, crops grown, and agricultural practices applied.

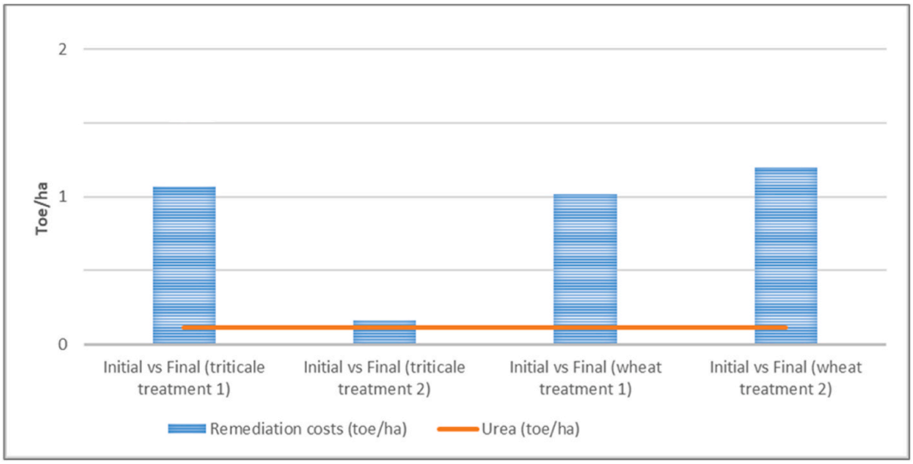

Fig. 5. Comparison of the exergy cost of the urea production and application and the soil regeneration cost necessary for each trial.

To better understand and contextualize the exergy cost values obtained for required remediation, we will compare them with the exergy cost of urea production and the exergy provided by the crop. Initially, Nitrogen stands out as the most crucial primary nutrient, constituting 54% of total consumption. Additionally, urea is classified among nitrogenous fertilisers, given its global significance and higher trade volume compared to ammonia (Yara, 2022). As detailed in Section 2.1, a value of 67.8 MJ/kg N is used as the average energy required for producing urea, including packaging and transportation. This study considers the amount of urea used in the agricultural process for obtaining the crops and the percentage of nitrogen in urea (46%). Therefore, 0.11 toe/ha of urea has been required for crop production as a basal fertiliser.

As shown in Fig. 5, in exergetic terms, all the conducted trials require more regeneration exergy than is consumed in urea production, packaging, and transportation, which is the most energy-intensive process required for agricultural production. The exergy needed for the regeneration processes ranges from above one to almost eleven times the energy required for the urea application. Thus, the energy and effort needed for the industrial process of urea production, including ammonia production, is comparatively lower than what is required to remediate and recover the nutrient loss in the soil observed in agricultural practices. In other words, the environmental and energy costs associated with industrial fertiliser production, even when as energy-intensive as urea, are surpassed by the energy and effort required to address the consequences of nutrient depletion in the soil caused by current agricultural practices. This result reveals the unsustainability and inefficiency of the agricultural process by demonstrating that the soil degradation caused by current agricultural practices requires more energy and effort for remediation than the energy and effort invested in the production and application of fertilisers, such as urea. Although the industrial process of fertiliser production consumes a significant amount of energy, the energy needed to restore the degraded soil is considerably greater. This indicates that agricultural production, as it is currently practised, is causing soil degradation so severe that its recovery demands a disproportionately large effort. The regeneration exergy cost of highlighted here emphasizes the need to adopt more sustainable agricultural methods that mitigate soil degradation.

Thus, the exergy methodology developed in this paper not only enables the quantification of the impact of agricultural practices on soil fertility—often overlooked in impact assessments of agricultural processes and crops—but also standardizes this concept alongside erosion assessment (Palacino et al., 2022) and the global exergy computation of the agro-ecosystem.

5. Limitations and future research perspectives

Fertile soils are a key resource of our planet but their complexity makes it difficult to achieve a comprehensive approach to quantify their loss of quality or degradation. The methodology proposed here aims to provide the basis for working in this direction, offering a single numerical indicator that can be unified with the agricultural system as a whole. To this end, the main innovation developed in this work is the concept of the exergy regeneration cost for soil remediation.

Although the initial results show consistent orders of magnitude, the methodology needs to be validated with a larger number of field trials and agricultural data for different crops, farming practices, and soil types. This will allow for a review of the terms under consideration and to add or modify those deemed critical.

In addition to its validation with numerical data, it is planned to keep the developed terms updated according to the conventions that will be established to monitor soils. While the focus of this methodology was on agricultural soils and their loss of fertility, it is also intended to expand it to a broader approach that encompasses soil health and the various ecosystem services it provides beyond fertility.

6. Conclusions

Soil degradation is a worldwide problem that must be evaluated in the sustainability assessment methodologies used for agriculture. Current agricultural practices are depleting soil at a rate that far exceeds the soil's natural capacity for regeneration. Thus, an exergy methodology has been developed to assess the soil system with a single indicator. In this work and its predecessor, exergy is proposed as a valuable tool to evaluate soil degradation and fertility.

This work proposes a methodology to quantify the loss of quality and degradation of agricultural soil after crop production using the exergy regeneration cost. Using exergy, it is possible to assign a value to restore the soil fertility parameters affected by crop production. To achieve this, processes capable of returning the final state of the soil to its initial state were simulated using the exergy regeneration cost. These exergy costs indicate the effort and work needed to return the soil to its initial conditions.

This methodology has been applied to field trial results, demonstrating that the magnitude of the regeneration cost is much higher than the energy consumption associated with the production and application of the most energy-intensive input, nitrogen. This shows that current agricultural practices are neither sustainable nor efficient, as they lead to soil degradation that demands a significantly greater effort to restore than the effort invested in crop production. The proposed methodology is a novel way to quantify this degradation and assist in adopting methods that minimize soil degradation and maximize resource use efficiency.

This is the first time that the use of exergy and the theory of exergoecology to quantify the value of fertile soils has been proposed, making it possible to evaluate and quantify the soil system before and after the agricultural process with a single parameter, exergy. Thus, soil degradation can no longer be neglected in the evaluation of agricultural sustainability. Furthermore, the prospect of assessing soil recovery processes in exergy terms not only facilitates their quantification but also allows for the harmonization of this concept within uniform units, also encompassing erosion and the comprehensive assessment of all the energy utilized in the agroecosystem.

CRediT authorship contribution statement

Barbara Palacino: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Sonia Ascaso:** Validation, Supervision, Methodology, Investigation. **Antonio Valero:** Writing – review & editing, Supervision. **Alicia Valero:** Writing – review & editing, Supervision.

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

The authors are unable or have chosen not to specify which data has been used.

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During the preparation of this work the author(s) used OpenAI (2024) version GPT-4 and Grammarly to detect and correct grammatical mistakes. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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