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Methodology to quantify the global agricultural crop footprint including soil impacts

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Contents

Page

European foreword

This CEN Workshop Agreement (CWA 17898:2022) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by a Workshop of representatives of interested parties on 2022-06-06, the constitution of which was supported by CEN following the public call for participation made on 2022-03-02. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

Loss of soil fertility and soil erosion are some of the threats facing mankind. Agricultural systems are complex systems made up of physical, chemical, and biological properties. Soil parameters or factors constitute these properties. A large number of factors involved in the cycles and processes occurring in the soil makes it necessary to study them using different parameters. Due to the complexity of soils, there is currently no consensus on how to assess loss of soil fertility and soil erosion, and they are not included in the usual environmental impact assessment methodologies.

This CWA proposes to use the exergy methodology to evaluate all the impacts of an agroecosystem, including those occurring in the soil. Exergy is a physical property based on the second law of thermodynamics and unifies into a single indicator; all soil parameters relevant for soil fertility assessment.

This CWA is an opportunity to further improve soil quality evaluation by introducing a thermodynamic indicator that will contribute to a rigorous assessment of agricultural processes' impact. The determination of a single comparable, reliable, accurate, and globally accepted indicator will be essential in the near future for the evaluation of soil fertility and agricultural processes efficiency and environmental sustainability.

1 Scope

This European CWA specifies a methodology for identifying, characterizing, and implementing a single indicator to assess the quality and degradation of agricultural soils and the overall impact of the agriculture processes. The agriculture impacts are assessed through the mechanical, fertilization and irrigation activities associated. Furthermore, soil impacts is evaluated accounting with soil erosion and parameters such as nutrients, texture, and organic matter. The developed methodology allows a simple but robust assessment of soil biogeochemical processes and the loss of fertility and degradation.

This European CWA also provides, in Annexes A and B, informative guidance on its use.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 20951:2019, *Soil Quality — Guidance on methods for measuring greenhouse gases (CO_2, N_2O, CH_4) and ammonia (NH_3) fluxes between soils and the atmosphere*

ISO 11063:2020, *Soil quality — Direct extraction of soil DNA*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
exergy
the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surrounding environment by a sequence of reversible processes

The exergy of a system gives an idea of its evolution potential for not being in thermodynamic equilibrium or dead state with the environment. Unlike mass or energy, exergy is not conserved but destroyed by irreversibilities and lost in all physical transformations until the system reaches a dead state.

Exergy is an extensive property with the same units as energy.

3.2
eco-exergy
the working capacity of organisms due to the genetic information they possess [1]

3.3
crop exergy footprint
CEF
the energy required, considering the irreversibility of the different processes, to carry out the different activities involved in the agricultural process

3.4
impacts on soil
IoS
the energy required, considering the irreversibility of the different processes, to incorporate and replenish substances from a state where the soil and its components have undergone modifications due to the agricultural process to the initial state of the soil

3.5
life cycle assessment
LCA
a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service

4 Measuring soil quality

4.1 The methodology's stakeholders

4.2 General overview of the methodology

The approach described is a comprehensive methodology for assessing the impacts of agricultural processes and their efficiency, including the evaluation of soil quality and its degradation during the process. The approach is based on detailed exergy analysis of the pre-and post-process soil condition of an agricultural production system for:

— studying the resources and allow their exergy calculation for subsequent analysis and evaluation of the worsening or improvement of the agricultural system status;

— defining process constraints and requirements for maintaining or improving the quality of the system;

— identifying the process parameters and select the critical process parameters for process control and optimization.

To apply the methodology, the system boundaries for the main system and parameters shall be defined to apply all steps based on the same scope to ensure comparable results.

In this methodology, Crop Exergy Footprint (CEF) and Impacts on Soil (IoS) are used to analyse and evaluate the agricultural process, including the different activities carried out during cultivation, such as tillage, fertilization, and application of amendments, irrigation, and erosion. By means of these factors, it is possible to describe the state and quality of the soil in different operational states.

A detailed methodology to evaluate the exergy loss due to soil erosion is shown as part of IoS. Diffuse emissions are also accounted for in CEF. The production obtained by the agroecological system is the main output. Accordingly, this methodology evaluates agroecosystem processes considering all exergy flows entering and leaving the system allowing for a detailed analysis of the parameters that may have been affected by crop generation.

The impacts on the agricultural soil are evaluated by means of the Impacts on Soil (IoS), which assesses the hypothetical cost to return the system from the final state to the initial state before the agricultural process. Understanding the fertility of soils as an avoided cost that nature provides leads us to propose exergy replacement cost as a tool for the assessment of the loss of soil fertility due to agriculture practices.

A methodology has been established to evaluate the system in order to reduce the number of variables to be analysed to assess the quality and status of the system.

For an overview of the methodology, see Figure 1.

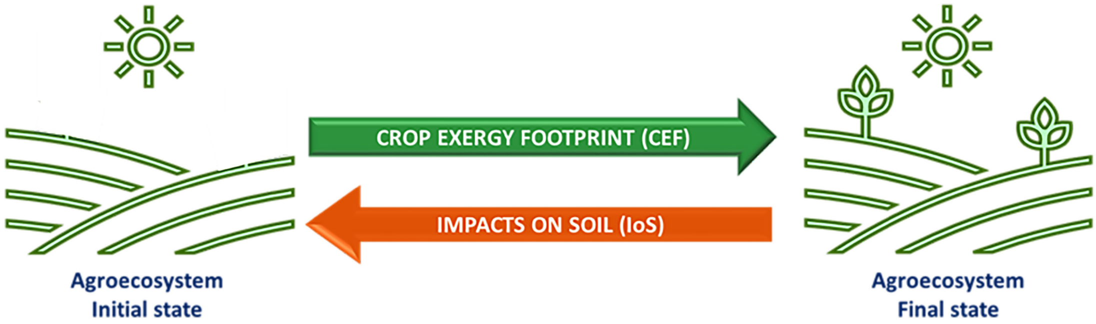

Figure 1 — Schematic overview of the methodology system

4.3 Process analysis

An essential step for the analysis and evaluation of soil quality and process impact is the definition of subfactors, which can be increased or decreased in value depending on their nature (used as an objective function for the evaluation). The methodology recommends the use of the following subfactors for the evaluation: mechanical processes, fertilizers, pesticides and phytosanitary supplies, water, erosion and soil losses and diffuse emissions in CEF. In the case of IoS, the use of the subfactors: nutrients amendment, organic matter amendment, salinity amendment, acidification amendment and erosion soil losses are recommended. These subfactors are described in the following sections and schematically represented in Figure 2 and Figure 3.

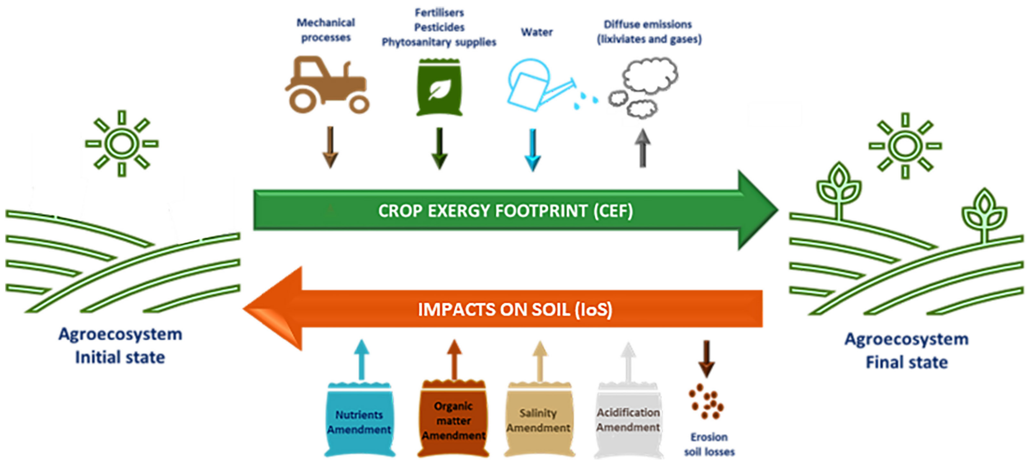

Figure 2 — Illustration of variables used for process and soil study and evaluation

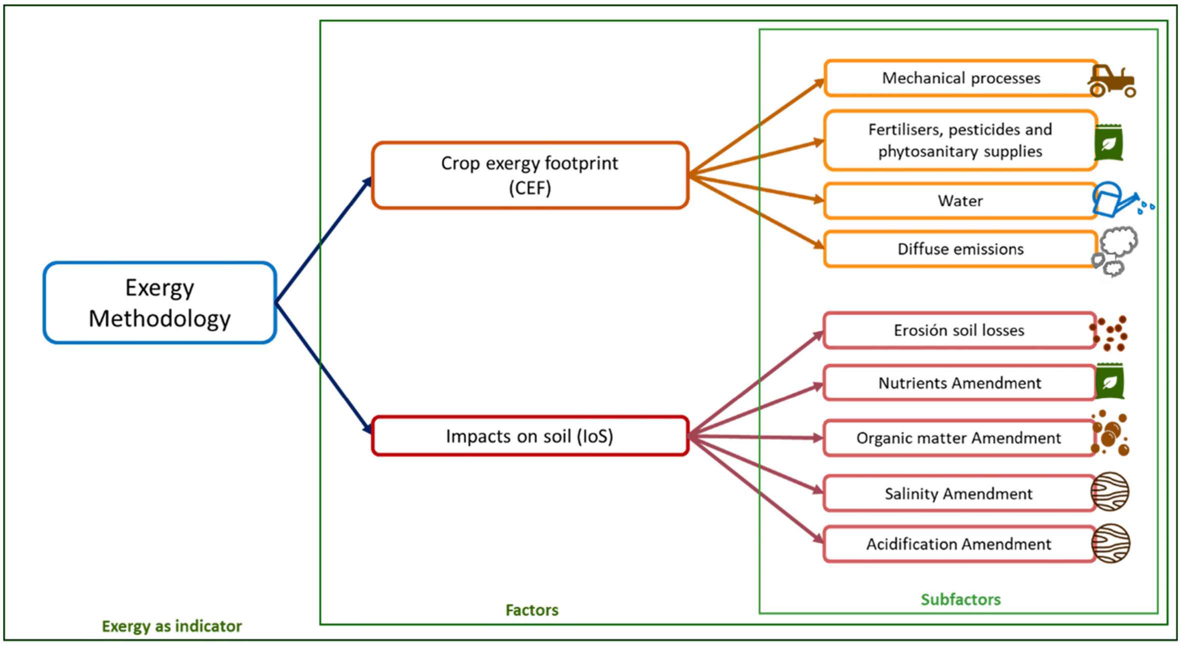

Figure 3 — Methodology concepts diagram

4.3.1 Crop exergy footprint (CEF)

4.3.1.1 General

The Crop exergy footprint (CEF) is the indicator that allows evaluating the energy needed to carry out the activities involved in the cultivation process, considering all the irreversibilities of the processes. This indicator is applied to the agroecosystem as a whole, evaluating all inputs and outputs to the field.

The following exergy inputs to the agricultural system are considered: water, fertilizers and other phytosanitary products, and the energy required in the different mechanical processes.

Two sets of subfactors shall be used within the methodology: Input Subfactors, which focus on the direct activities and processes that are performed on the cultivation system, and Output Subfactors, which focus on environmental impacts associated with the agricultural activities.

Three Input Subfactors are proposed to constitute the main CEF in the methodology:

— Mechanical processes [MJ/ha].

— Fertilizers, pesticides, and phytosanitary products [MJ/ha].

— Water [MJ/ha].

$\boldsymbol{CEF_1 = Mechanical\ processes + Fertilizers,\ pesticides + Water}$

Where "ha" stands for hectare, which represents the quantity of the main soil of the process under study.

These subfactors provide information on the three main activities used: tillage, irrigation, and fertilization. The exergy indicator alone covers all these processes and provides a quality-weighting factor based on rigorous thermodynamics.

Output subfactors are proposed to constitute the CEF in the methodology:

— Diffuse emissions [kg Element/ha].

CEF_2 = Diffuse emissions

This subfactor is selected to focus on the environmental impact of the agricultural processes. Diffuse emissions complement the Input Factors and allow a joint and global evaluation of the whole process.

All of these subfactors are detailed in the following sections.

4.3.1.2 Mechanical processes

This subfactor is defined as the activities and tasks necessary to prepare the system and improve its capacities and qualities before and after cultivation. Mechanical processes include tillage, sowing, fertilizing, and harvesting. They are responsible to a great extent for the energy consumed in agriculture.

There are two options for the estimation, option 1: when energy consumption in terms of fuel is known; option 2: when no energy consumption is known (Figure 4).

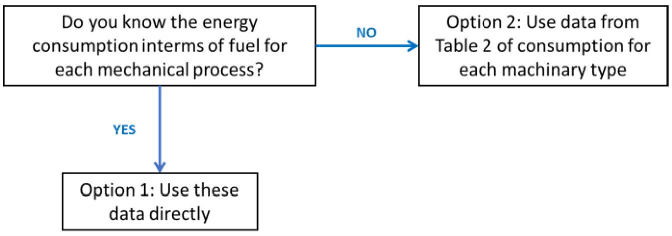

Figure 4 — Diagram explaining the method of calculating the energy consumed during the mechanical process based on the different possible starting data available

The exergy of the mechanical processes (Ex) is proportional to the amount of fuel used (Formula 1). If this amount is known, the conversion to energy units will be performed.

$$Ex\left(\frac{MJ}{ha}\right) = \frac{Fuel\,(l)\cdot Density\left(\frac{kg}{l}\right)\cdot HHV\left(\frac{MJ}{kg}\right)}{Land\ surface\,(ha)} \qquad (1)$$

If the real amount of diesel used is unknown, the following values for the HHV (High Heating Value) and density shall be used (Table 1).

Table 1 — High heating value (HHV) of fuels

	Diesel
HHV (MJ/kg)	45.6
Density (kg/l)	0.84

Tillage processes demand the largest amount of energy, depending on the type of soil and depth of the process. According to the study performed by IDAE [2], the exergy due to different types of tillage can be found in Table 2; a simple classification is made according to texture, light (corresponding to sandy and loamy textures), and heavy (corresponding to clay textures).

Figure 5 shows how the classification of textures is divided according to whether they are considered light or heavy, showed in green or brown, respectively.

A classification is made according to the working depth, which can be either high or low, for depths higher than 15 cm or lower than 15 cm, respectively. However, the classification of low or high depth will depend on each tillage activity and on the working machinery and its technical specifications.

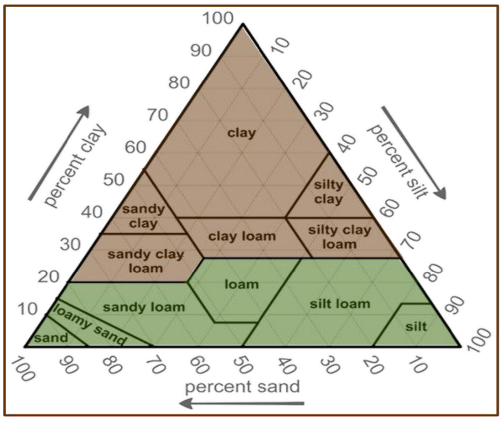

Figure 5 — Texture classification scheme, showing the division between light textures (green) and heavy textures (brown)

In the case of fertilizer or amendment application processes and the seeding process in the cropping system, a data collection shall be used (Table 2), distinguishing two consumptions, which are related to the width of the implement and work in the labour or application rate of the product, called "Normal" and "High". Exergy values according to the doses of product applied should be estimated, based on dose data (kg/ha or l/ha) (Formula 2).

$$Ex\left(\frac{MJ}{ha}\right) = \sum Machinery\ energy\left(\frac{MJ}{ha}\right) \quad (2)$$

Regarding the machinery, within the group of harvesters, there are different types depending on the type of crop (corn, cereal, sunflower, among others). Data are also available for balers, windrowers, and mowers (Table 2).

Table 2 — Energy data on the consumption of tillage implements, seed drills, and harvesters

	Energy (MJ/ha)			
	Light/low	**Light/high**	**Heavy/low**	**Heavy/high**
Subsoiler	687,01	877,85	1 030,51	1 145,02
Mouldboard plow	687,01	839,68	992,35	1 145,02
Disc plow	572,51	725,18	877,85	1 030,51
Chisel plow	343,50	458,01	572,51	687,01
Rolling cultivator	458,01	534,34	687,01	763,34
Disc harrow	229,00	267,17	343,50	381,67
Spring tine cultivator	152,67	229,00	305,34	381,67
Vibrocultivators	229,00	229,00	229,00	229,00
Spike-tooth harrow	190,84	190,84	190,84	190,84

	Energy (MJ/ha)		
	Normal	High	
Centrifugal spreader	57,25	28,63	
Locator spreader	229,00	152,67	
Row seed drill	267,17	152,67	
Direct row seed drill	419,84	229,00	
Single seed drill	248,09	171,75	
Direct single seed drill	267,17	190,84	
Inter-row cultivators - Spreader	171,75	133,59	
Inter-row cultivators	171,75	133,59	
Roller	190,84	152,67	
Hydraulic spray	41,98	28,63	
Spray pump	152,67	76,33	
Manure distributor trailer	267,17	190,84	
	Dose (kg/ha o l/ha)	**Energy (MJ/kg)**	
		Normal	**High**
Centrifugal spreader	250,00	0,229	0,115
Row seed drill	140,00	1,908	1,090
Direct row seed drill	145,00	2,895	1,579
Inter-row cultivators - Spreader	200,00	0,859	0,668
Hydraulic spray	250,00	0,168	0,115
Spray pump	850,00	0,180	0,090
	Energy (MJ/ha)		
	Normal	**High**	
Cereal harvester	572,51	343,50	
Corn harvester	763,34	458,01	
Sunflower harvester	305,34	152,67	
Sugar beet leaf stripper	458,01	381,67	
Sugar beet uprooter	343,50	267,17	
Sugar beet loader	419,84	305,34	
Potato harvester	1 259,52	954,18	
Rotary mowers	286,25	229,0	
Cutter bar	286,25	229,0	
Mower conditioner	267,17	229,0	
Fodder windrow rake	152,67	38,17	

Packer (conventional)	381,672	209,92
Loading bales	45,80	30,53
Wrapping machine	95,42	76,33
Self-loading trailer	95,42	57,25
Hay combine harvester	954,18	763,34
Corn combine harvester	1 374,02	1 030,51

4.3.1.3 Fertilisers, pesticides and phytosanitary supplies

The exergy embodied in all the processes associated with the production of fertilizers, pesticides, and any other phytosanitary supplies applied to the agroecosystem needs to be accounted for. The energy consumed in the transport of the raw materials to the factory and then to the field are also considered. If detailed information is known, this can be calculated for each situation following a life cycle assessment approach (Figure 6). If not, this methodology provides average data for each nutrient obtained after a careful revision of bibliography sources[3], [4], [13]–[15], [5]–[12]; Ecoinvent 3) furthermore a constant transport distance of 500 km in rail and 400 km by trail is considered[16], [17] (Table 3).

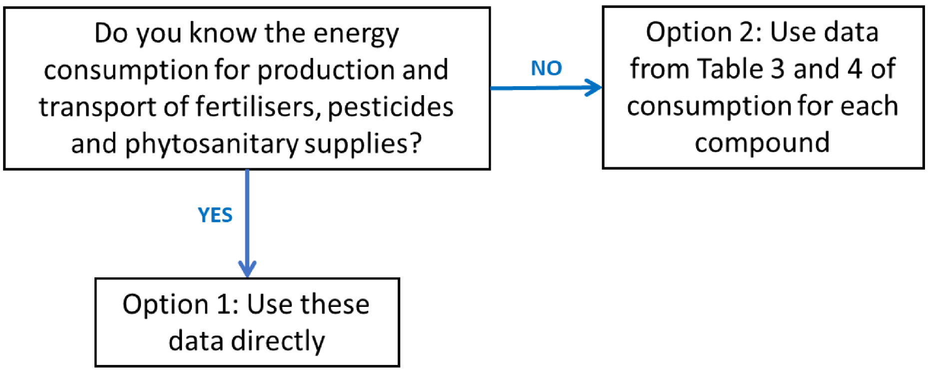

Figure 6 — Diagram explaining the method of calculating the energy consumed during the mechanical process based on the different possible starting data available

Formula 3 should be applied if option 1 is possible, through the data on the nutrient content of the fertilizers used, the fertilizer dose applied, and the exergy involved in the production of the nutrient (Table 3).

$$Ex\left(\frac{MJ}{ha}\right) = \sum\left(\text{Nutrient content in compound}\left(\frac{kg\ Nut}{kg\ comp}\right)\cdot \text{Dose}\left(\frac{kg\ comp}{ha}\right)\cdot \text{Exergy nutrient}\left(\text{Table 3}\right)\left(\frac{MJ}{kg\ Nut}\right)\right) \tag{3}$$

Table 3 — Average exergy contribution associated to the production and transport of nutrients

Inorganic nitrogen	**67,8**	**MJ/kg N**
Phosphorus	50,87	MJ/kg P
Potassium	15,06	MJ/kg K
Calcium	22,89	MJ/kg Ca
Magnesium	31,2	MJ/kg Mg
Copper	222,94	MJ/kg Cu

Iron	9,25	MJ/kg Fe
Manganese	73,08	MJ/kg Mn
Zinc	28,77	MJ/kg Zn
Gypsum	3,7	MJ/kg S
Limestone	2,3	MJ/kg Ca

In the case of pesticides, if detailed information is known, this can be calculated for each situation following a life cycle assessment approach. If not, this methodology provides data for each pesticide obtained after a careful revision of bibliography sources (Ecoinvent 3) (Table 4).

Table 4 — Average exergy contribution associated to the production of pesticides

	Exergy (MJ/kg)
Carbofuran	118,36
Carbaryl	281,31
Cypermethrin	226,22
Chlordimeform	86,4
Malathion	348,57
Paration	232,07

4.3.1.4 Water

Water supplied by rain is not always enough for crop, and irrigation processes are needed. In this methodology, the exergy of the water will be calculated as the energy consumed in the irrigation processes associated. Irrigation processes consume large amounts of energy (Formula 4).

$$Ex\left(MJ\right) = Water\ consumption\left(m^3\right) \cdot energy\ consumption\left(\frac{kWh}{m^3}\right) \cdot 3,6 \qquad (4)$$

If data about the type of irrigation process is available, the energy consumption shown in Table 5 will be used.

Table 5 — Energy consumption (kWh/m^3) related to the type of irrigation carried out [18]

	Irrigation system	**Capture (kWh/m^3)**		**Transport and treatment (kWh/m^3)**			**Total (kWh/m^3)**	
		Surface	**Underground**	**Transfer**	**Desalination**	**Reuse**	**Irrigated land**	**Transport and treatment**
Gravity	0	0,02	0,15	1,2	3,7	0,25	0,04	0,07
Sprinkling and automotive	0,24	0,05	0,25	1,2	3,7	0,25	0,35	0,35
Local	0,18	0,1	0,5	1,2	3,7	0,25	0,43	0,53
AVERAGE	0,14	0,06	0,30	1,20	3,70	0,25	0,27	0,32

If the type of irrigation process is unknown, average data will be obtained from Table 6.

Table 6 — Average energy consumption considered

Water cycle processes in agriculture	Aspects considered	kWh/m^3
Pump	Surface water	0,555
	Groundwater	0,633
Supply and transport	General	1,200
Distribution	General	0,232
TOTAL	**Surface water**	**1,99**
	Groundwater	**2,07**

Analyzing the consumption of irrigation water and the number of different crops in Spain using INE (Instituto Nacional de Estadística. *Spanish National Statistical Institute*) Table 7 was obtained. These data shall be used if the amount of water used is unknown, but the crop type is available.

Table 7 — Water consumption according to a type of irrigation and crop

Area by Crop Groups and type of Irrigation Spain 2018	Gravity area (m^3/ha)	Sprinkling area (m^3/ha)	Drip surface (m^3/ha)
Herbaceous	4.778	3.873	87
Potatoes and vegetables	573	716	254
Fruit trees	843	29	719
Olive grove and vineyards	422	56	1.540
Other crops type	285	20	64
TOTAL	**6 901**	**4 695**	**2 663**

If there is no knowledge of the type of irrigation and water consumption, it is possible to roughly estimate the amount of water consumed per crop, irrespective of the type of irrigation (Table 8).

Table 8 — General water consumption, irrespective of the type of irrigation, depending on the type of crop

Crop type	Area (ha)	General irrigation (m^3/ha)
Herbaceous	1 285 835	6 584
Potatoes and vegetables	379 119	6 812
Fruit trees	639 457	1 860
Olive grove and vineyards	1 208 058	1 428
Other crops type	211 726	7 234
TOTAL	**3 724 195**	**23 918**

Figure 7 describes the calculation process necessary to estimate the energy consumed during the irrigation process, depending on the starting data available.

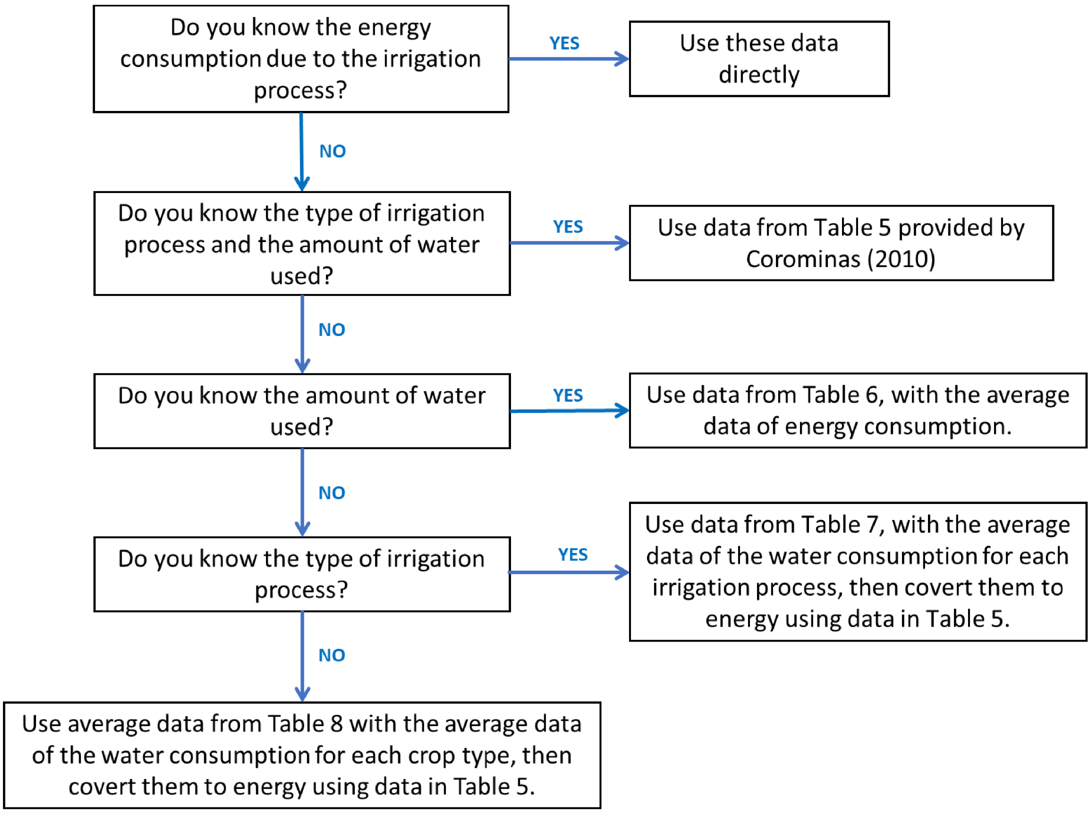

Figure 7 — Diagram explaining the method of calculating the energy consumed during the irrigation process based on the different possible starting data available

4.3.1.5 Diffuse emissions

When nutrients are applied to soil, the generation of different emissions takes place. Nitrogen is the leading emitter generating gaseous emissions of ammonium, nitrous, and nitrogen oxides.

Due to the diffuse character of the emission, its quantification is difficult. Values of emission factors associated with different fertilizer products are not always available. The standard ISO 20951:2019 explains experimental methods to quantify the emissions. If it is not possible to obtain these values, the methodology explained here shall be used (Table 9).

For ammonium, if a revised emission factor is not available, the factor proposed by [19] should be used.

Table 9 — Emission factor for each fertilizer

Fertilizer type	Emission factor NH_3/N (%)
Ammonium nitrate	2
Ammonium sulfate	8
Urea	15
Multi-nutrient fertilizers (NPK-, NP-, NK-)	4
Urea ammonium nitrate	8,5
Liquid ammonium	3

Nitrogen emitted as NO_3^- to subterranean water depends on the climatology and period of the years as it is very dependent on rainfall. If real data is not available, this methodology will use the following formula [20], [21]:

$$N\left(\frac{kg\,N}{ha\cdot year}\right) = 21,37 + \frac{P}{c\cdot L}\left[0,0037\cdot S + 0,0000601\cdot N_{org} - 0,00362\cdot U\right] \quad (5)$$

where

N is leached NO^{3-}N (kg N /ha·year);

P is precipitation plus irrigation (mm/year);

c is clay content in percentage (%);

L is rooting deph (m);

S is nitrogen supply through fertilisers (kg N/ha);

U is nitrogen uptake by crop (kg N/ha);

N_{org} is nitrogen in organic matter (kg N/ha):

$$N_{org} = \left(\frac{C_{org}}{100}\cdot V\cdot D_b\right) / r_{\frac{C}{N}}\cdot r_{Norg} \quad (6)$$

where

V is soil volumen (m^3/ha);

D_b is total density;

$r_{C/N}$ is ratio C:N equal to 11 if not specific data is available [22];

r_{Norg} is ratio N organic/N total equal to 0,85 if not specific data is available.

N_2O is emitted into the air, and its estimation is very uncertain. If more specific data are not available, the estimation proposed by [23] in Formula 7 shall be used.

$$N_2O\left(\frac{kg\,N_2O}{ha\cdot year}\right) = \frac{44}{28}\cdot\left[0,01\cdot\left(N_{tot} + N_{cr}\right) + 0,01\cdot\frac{14}{17}\cdot NH_3 + 0,0075\cdot\frac{14}{62}\cdot NO_3^-\right] \quad (7)$$

where

N_{tot} is total nitrogen in mineral and organic fertilizers (kg N/ha);

N_{cr} is nitrogen contained in harvest residues (kg N/ha);

NH_3 is nitrogen losses in the form of ammonia (kg NH_3/ha);

NO_3^- is nitrogen losses as nitrate (kg NO_3^-/ha).

NO_x emitted is estimated as [22] (Formula 8):

$$NO_x\left(\frac{kg\ NO_x}{ha\cdot year}\right)=0{,}21\cdot N_2O \tag{8}$$

4.3.2 Impacts on soil (IoS)

4.3.2.1 General

Understanding the fertility of soils as an avoided cost that nature provides without charge leads us to propose Impacts on soil (IoS) as a tool for the assessment of the loss of soil fertility due to agriculture practices. Exergy is used to calculate the energy embodied in a simulated replacement process that may recover the impact on fertility.

This methodology proposes that the quality or fertility of soil can be restored with the proper recovery of nutrients, organic matter, microorganisms, salinity, and acidification. This allows the measurement by means of exergy of the reposition needed after an agricultural process. This term is added to the rest of the agroecological process as the unifying unit used is exergy.

A set of subfactors shall be used within the methodology: The Amendment Subfactors, which focus on the assessment of the state of the different selected parameters and their recovery to initial levels if they have been minimized due to agricultural practices.

— Four Amendment Subfactors are proposed to constitute the main IoS in the methodology:

— Nutrients Amendment.

— Organic matter Amendment [MJ/ha].

— Salinity Amendment.

— Acidification Amendment.

IoS*$_1$ *= Nutrients Amendment + Organic Matter Amendment + Salinity Amendment + Acidification Amendment

These subfactors provide information on the main soil nutrient cycles and have been selected to focus on the environmental impact of the agricultural processes.

— Output Subfactors, which focus on soil losses impacts associated with the agricultural activities

  — Erosion soil losses [MJ/ha·year]

IoS*$_2$ *= Erosion soil losses

The estimation of the IoS is needed to replenish the impacts of the agricultural process will be made by comparing the final state of the soil with the initial state prior to the start of plowing. The quantity of each selected factor will be analysed, and the need for replacement will be assessed. If the final state of the factor is higher than the initial state, no replenishment will be necessary. If the final state is lower than the initial state, the soil will have suffered a deterioration of its properties, and therefore, it will be necessary to calculate the Impacts soil (IoS).

All of these factors are detailed in the following sections.

4.3.2.2 Nutrients Amendment

The flow of nutrients from the soil to the plants allows their growth. The movement of nutrients in the soil is a complex process influenced by many soil and plant properties. An adequate level of each nutrient in the soil is the first requisite. This is obtained using mineral or organic fertilizers. In this methodology, the cost associate with the reposition of nutrients is calculated as the energy needed in the production of the inorganic fertilizer, its transport, and distribution. Furthermore, the emissions generated due to the application of the fertilizers in the field are considered.

Formula 9 should be used for the calculation of nutrient content needed for the quantity of amendment. Formula 10 should be applied for estimate the Nutrient Amendment (MJ/ha) based on the result of Formula 9, the fertilizer production cost (exergy, Table 10), mechanical fertilizer application process (Table 2) and nutrient concentration of the fertilizer (Table 11).

$$Nutrient\left({kg}/{ha}\right) = Variation\ content\left({kg\ Nutrient}/{kgsoil}\right) \cdot 10.000\frac{m^2}{ha} \cdot 0,3m \cdot 1.400\,{kgsoil}/{m^3} \tag{9}$$

$$\begin{aligned} Nutrient\ Amendment\left(MJ\ /\ ha\right) &= Nutrient\left(\frac{kg\ Nut}{ha}\right) \cdot Fertilizer\ prod.Cost\left(\frac{MJ}{kg\ Nut}\right) \\ &+ \frac{Fert.mechanical\ process\left(\frac{MJ}{kg\ fert}\right) \cdot Nutrient\left(\frac{kg\ Nut}{ha}\right)}{Fertilizer\ nutrient\ concentration\left(\frac{kg\ Nut}{kg\ fert}\right)} \end{aligned} \tag{10}$$

The most representative energy value for each nutrient is shown in Table 10:

Table 10 — Exergy needed for nutrients amendment

Nitrogen (inorganic)	**67,8**	**MJ/kg N**
Phosphorus	50,87	MJ/kg P
Potassium	15,06	MJ/kg K
Calcium	22,89	MJ/kg Ca
Magnesium	31,2	MJ/kg Mg
Copper	222,94	MJ/kg Cu
Iron	9,25	MJ/kg Fe
Manganese	73,08	MJ/kg Mn
Zinc	28,77	MJ/kg Zn

These data are the energy embodied in all the processes associated with the production of fertilizers. Also, the energy consumed in the transport of the raw materials to the factory and then to the field [3], [4], [13]–[15], [5]–[12].

In addition to these data, the cost of field distribution will also be estimated. This value will be calculated from the energy consumption established for the normal centrifugal spreader (0,229 MJ/kg fertilizer) and considering the quantity of fertilizer to be distributed. The amount of fertilizer is calculated from the composition of each nutrient in the most used mineral fertilizers and with only one nutrient per compound (Table 11).

Table 11 — Content for each nutrient in the most used fertilizers

	Product/Fertilizer	Nutrient content (kg element/kg compound)
Nitrogen (inorganic)	Urea	0,46
Phosphorus	Triple superphosphate (TSP) – single superphosphate (SSP)	0,144
Potassium	Potassium chloride	0,498
Calcium	Calcium nitrate	0,186
Magnesium	Magnesium sulfate	0,0999
Copper	Copper sulfate	0,25
Iron	Iron sulfate	0,2
Manganese	Manganese sulfate	0,32
Zinc	Zinc sulfate	0,28

The calculation of Nutrients Amendment will be calculated based on the following formulas. For the conversion of kg soil to hectares, a soil density of 1 400 kg/m^3 and a depth of 0,3 m is considered as this is a topsoil study.

4.3.2.3 Organic matter (OM) Amendment

Organic matter content is highly relevant in soil fertility because it influences the physical, chemical, and biological properties of soil. Organic matter is linked to the structure, the nutrients cycles, cationic exchange capacity, pH, and microorganism activity, among other aspects. Furthermore, the stability of OM in soils is directly related to its capacity to store carbon, avoiding CO_2 emissions.

Subproducts and wastes represent one of the main sources of OM that is applied to soils. It can be applied directly or after a stabilization process as composting. Compost is selected as representative of the repositioning of organic matter. Windrow composting, where long rows of OM are pile, is the most representative one. 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 will be small as it is usually applied close to the point of production.

Formula 11 should be used for the calculation of organic matter content needed for the quantity of amendment. Formula 12 should be applied for estimate the Organic Matter Amendment (MJ/ha) based on the result of Formula 11, the compost exergy (Table 12) and mechanical fertilizer application process (Table 2).

$$OM\left(\frac{kg}{ha}\right) = \frac{\%Variation}{100}\left(\frac{kg}{kg\ soil}\right)\cdot 42\,000\,000\,\frac{kg\ soil}{ha} \qquad (11)$$

$$Organic\ Matter\ Amendment\left(MJ\ /\ ha\right)=\frac{OM\left(\frac{kg}{ha}\right)\cdot\left[Compost\left(\frac{kJ}{kg}\right)+Fert.mechanical\ process\left(\frac{kJ}{kg}\right)\right]}{1\,000\frac{kJ}{MJ}} \tag{12}$$

The OM Amendment in soils is going to be calculated as the energy needed in the composting process, the transport, and application in fields, considering a value of 10% assimilation rate of organic matter in the soil. This factor is defined as the percentage of organic matter applied to the soil that decomposes and recalcitrates to form part of the soil organic matter [24] (Table 12).

Table 12 — Exergy of organic matter amendment

	Exergy (MJ/kg)	**Conversion factor**
Compost	0,076	10 %

In addition to these data, the cost of field distribution will also be estimated. This value will be calculated from the energy consumption established for the normal centrifugal spreader (0,229 MJ/kg fertilizer).

4.3.2.4 Salinity Amendment

In some lands, irrigation water contained salts that accumulate in soils. This effect is worse in arid regions-high levels of sodium hamper plant growth. Among the different treatments to improve soil salinity, gypsum addition is simulated to calculate the repositioning cost. Gypsum ($CaSO_4 \cdot 2H_2O$) addition allows the exchange of Na^+ ions by Ca^{2+} decreasing salinity.

Formula 13 should be used for the calculation of sulphur content needed for the quantity of amendment based on the EPS (Exchangeable Proportion of Sodium) calculated (Formula 15). Formula 14 should be applied for estimate the Salinity Amendment (MJ/ha) based on the result of formula 13, gypsum production exergy (Table 13), mechanical fertilizer application process (Table 2) and gypsum nutrient content (Table 13).

$$Sulphur\left({}^{kg}\!/\!_{ha}\right)=\left(\frac{EPS_{final}-EPS_{initial}}{100}\right)\cdot CEC\cdot 873,6 \tag{13}$$

$$Salinity\ Amendment\left(\frac{MJ}{ha}\right)=Sulphur\ amendment\left(\frac{kg}{ha}\right)\cdot Fertilizer\ prod.\ cost\left(\frac{MJ}{kg\ S}\right)+ \\ +\frac{Fert.\ mechanical\ process\left(\frac{MJ}{kg\ fert}\right)\cdot Sulphur\ amendment\left(\frac{kg}{ha}\right)}{Gypsum\ nutrient\ content\left(\frac{kg\ S}{kg\ compound}\right)} \tag{14}$$

If the sodium proportion is high, the soil is defined as sodic (EPS >15). In this case, plant growth is hindered. The growth of sensitive plants is affected when the EPS is around 5 [25]. The value of the EPS factor is estimated from the following formula, where CEC is the cation exchange capacity of the soil:

$$EPS\left(\%\right) = \frac{Na\left(meq\ /\ 100g\right)}{CEC\left(meq\ /\ 100g\right)} \cdot 100 \tag{15}$$

This is applied when EPS>5 because sensitive plants decrease yield when the level of sodium is around 5 EPS. Due to the impurities in the gypsum and the inefficiency of the process in general, these quantities are adjusted with an extra 30 % gypsum in practice to take into account that the reactivity is not complete [25].

Table 13 — Exergy and sulphur content of gypsum

Gypsum	Exergy	3,7	MJ/kg S
	Content	0,186	kg S/kg compound

The Salinity value will be calculated from the energy consumption established for the normal centrifugal spreader (0,229 MJ/kg fertilizer) and considering the quantity of compound to be distributed (Table 13).

4.3.2.5 Acidification Amendment

Soil acidification affects a wide range of properties, from the capacity of plant roots to take up nutrients to the activity of soil microorganisms. The oxidation of ammonium-based fertilizers or some organic materials can produce soil acidification. To decrease soil acidity, the most common solution is to amend the soil with alkaline materials, referred to as agricultural limes. Apart from the pH change required, the amount of liming material needed is determined by several intrinsic factors as the buffer capacity of the soil or the exchangeable aluminium saturation. Also, the chemical composition and the grinding of the liming material. Following an approximation obtained by [25] for different types of soils, values of the amount of ground limestone need to raise the pH to 6.5 are obtained.

Formula 16 should be used for the calculation of calcium content needed for the quantity of amendment. Formula 17 should be applied for estimate the Acidification Amendment (MJ/ha) based on the result of formula 16, limestone production exergy (Table 14), mechanical fertilizer application process (Table 2) and limestone nutrient content (Table 14).

$$Calcium\ amendment\left({}^{kg}\!/\!{}_{ha}\right) = CaCO_3\left({}^{cmol_c}\!/\!{}_{kg\ soil}\right)\cdot 1638 \tag{16}$$

$$Acidification\ Amendment\left(\frac{MJ}{ha}\right) = Ca\left(\frac{kg}{ha}\right)\cdot Fertilizer\ prod.\ cost\left(\frac{MJ}{kg\ Ca}\right) + \\ + \frac{Fert.\ mechanical\ process\left(\frac{MJ}{kg\ fert}\right)\cdot Calcium\ amendment\left(\frac{kg}{ha}\right)}{Limestone\ nutrient\ content\left(\frac{kg\ Ca}{kg\ compound}\right)} \tag{17}$$

The following figure 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 on the curve to which the soil under study refers, and the amount of $cmol_c$ limestone/kg soil required to change the soil pH is estimated.

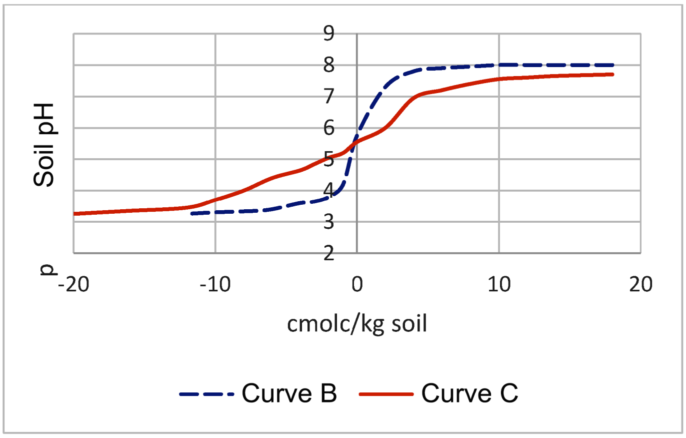

Figure 8 — Buffering of soil pH. Curve B, for soils with lower clay and organic matter content, curve C, for soils with higher organic matter and clay content. Adapted from [25]

To estimate the Acidification Amendment, starting from the amount of limestone required, the equivalent amount of calcium is estimated, and the exergy is applied directly to the calculated amount.

Table 14 — Exergy and the amount of calcium in limestone

Limestone	Exergy	2,3	MJ/kg Ca
	Content	0,39	kg Ca/kg compound

The Acidification Amendment value will be calculated from the energy consumption established for the normal centrifugal spreader (0,229 MJ/kg fertilizer) and considering the quantity of compound to be distributed (Table 14).

4.3.2.6 Erosion soil losses

The erosion process is one of the most complex phenomena to evaluate, but at the same time, it is one of the phenomena that most affects crop systems. The erosion suffered in a given area can be measured experimentally; however, due to the difficulty involved, the most widespread calculation method is the use of models that take into account the different factors involved in erosion processes.

The amount of soil lost through erosion will be calculated using a known and widely used methodology (4.3.2.6.1 Soil erosion) and, on this basis, the equivalent amount of erosion is calculated (4.3.2.6.2 Soil exergy) (Formula 18).

$$Erosion\ soil\ losses\left(\frac{toe}{ha\cdot year}\right) = Soil\ losses\left(\frac{t}{ha\cdot year}\right)\cdot\frac{Soil\ exergy\left({}^{toe}\!/\!{}_{kg}\right)}{1000\left({}^{t}\!/\!{}_{kg}\right)} \qquad (18)$$

4.3.2.6.1 Soil erosion

The models that determine erosion have been extensively studied, and although there are several approaches, the most recognized model is the Universal Soil Loss Equation (USLE) [26]. In this methodology, the USLE model, along with the later modified and further adapted version, RUSLE [27], shall be used to estimate the amount of soil lost by the erosion process.

These empirical models estimate the average erosion rate of soil from a combination of factors. The RUSLE model determines annual soil erosion (A) according to six factors (Formula 19):

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{19}$$

where

- A is the average soil loss per unit area (t/ha·year);
- R is the rainfall erosion factor (MJ mm/h·ha·year);
- K is the soil possibility factor (t·h/MJ·mm);
- L is the slope length factor (dimensionless);
- S is the slope steepness factor (dimensionless);
- C is the management and cover factor (dimensionless);
- P is the supporting practices factor (dimensionless).

As can be seen, each factor depends on the characteristics of the soil being studied in each case and its geographic location, and the type of agricultural processes applied to it.

Figure 9 describes the data needed to estimate each factor of the amount of soil that may be lost to erosion due to climatic, physical, and mechanical factors in a year.

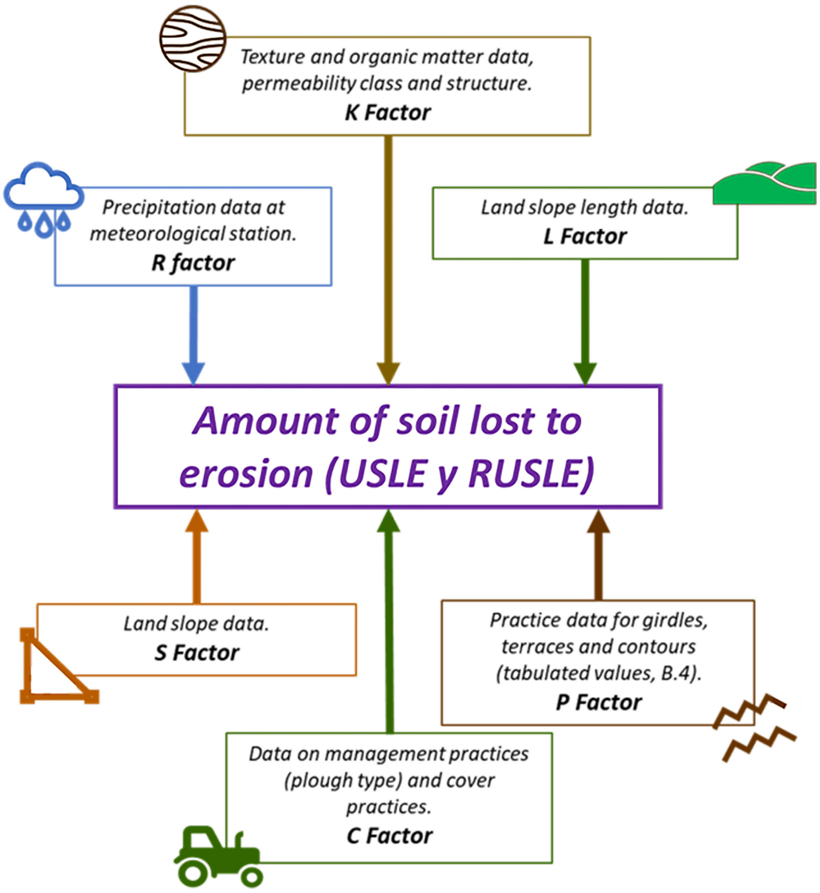

Figure 9 — Diagram explaining the data needed to estimate each factor involved in calculating the amount of soil lost to erosion. For further information, see Annex B

4.3.2.6.2 Soil exergy

To calculate and estimate the exergy of soil loss due to soil erosion generated by tillage, the amount of soil loss due to erosion (A) and the exergy of the soil will be considered. In this way, the exergy value of the erosion will be obtained from the amount of soil lost and the total exergy value of the soil.

The estimation of the exergy value of the soil is based on the physical, chemical, and biological properties of the soil. Considering that soil is a complex system, a parameter representative of soil's physical, chemical, and biological properties is selected (Formula 20).

$$\textit{Soil Exergy} = \textit{Texture input} + \textit{Nutrients input} + \textit{Organic matter input} + \textit{Microorganisms input} \tag{20}$$

Texture is selected to represent the physical properties, nutrients are selected to describe the chemical properties, and microorganisms are selected as the most important parameter within the biological properties. In addition, organic matter is selected as an overall parameter, as it acts both on physical properties, chemical properties, and biological properties.

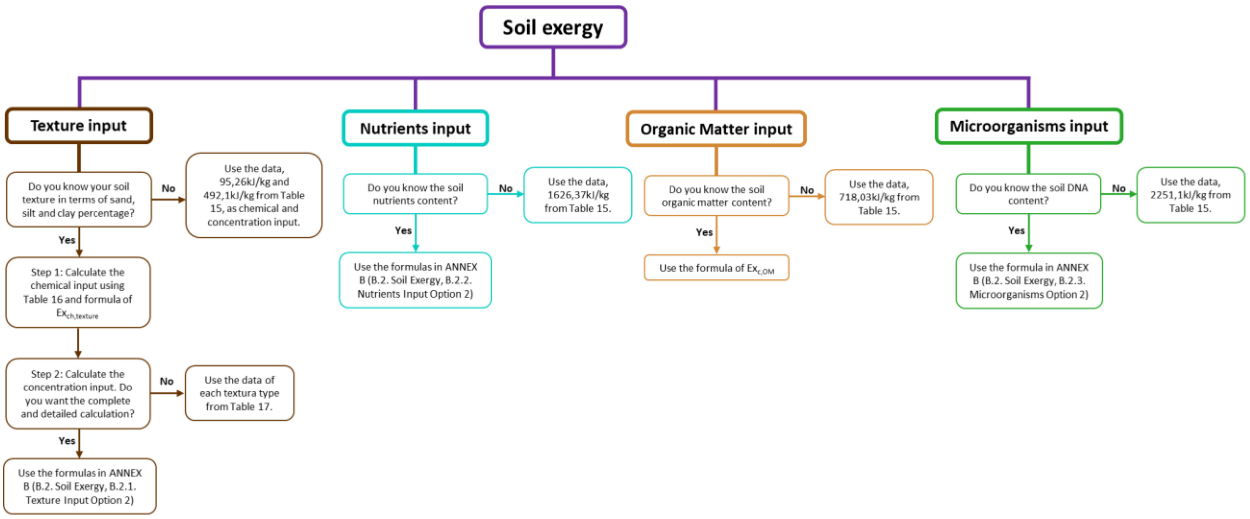

Figure 10 — Diagram explaining the method of calculating soil exergy based on the different possible starting data available

If no data are provided or a quick estimate of soil exergy is preferred, the data in Table 15 should be taken. These data considered optimal values for each parameter (Annex A, A.1 General), which corresponds to a conservative approach. This conservative state involves a higher value for erosion soil losses (Figure 10).

Table 15 — Values established for the conservative option

		kJ/kg
Texture	Chemical Input	95,26
	Concentration Input	492,10
Nutrients	Input	1 626,37
Organic Matter	Input	718,03
Microorganisms	Input	2 251,1

Texture is made up of the sum of two types of contributions, the chemical input, and the concentration input (Formula 21).

$$Texture\ input\ = Texture\ chemical\ input\left(Ex_{c,texture}\right) + Texture\ concentration\ input\left(Ex_{ch,texture}\right) \qquad (21)$$

The chemical input of the three main fractions of soil particles can be calculated from the following table of sand, silt, and clay fractions (Table 16).

Table 16 — Chemical input of sand, silt, and clay as the three components of soil texture

	(kJ/kg)
Sand	47,32
Silt	107,67
Clay	166,33

Taking into account the values of the three particle sizes that form the soil texture (Table 10), the chemical input of the texture of any soil can be calculated (Formula 22):

$$Ex_{ch,texture}\left(kJ\ /\ kg\right) = \left[\frac{\%\cdot 47,32kJ\ /\ kg}{100}\right]_{sand} + \left[\frac{\%\cdot 107,67kJ\ /\ kg}{100}\right]_{silt} + \left[\frac{\%\cdot 166,33kJ\ /\ kg}{100}\right]_{clay} \qquad (22)$$

The concentration input of one of the soil-forming minerals is calculated as the difference between the mineral concentration in the studied soil and the average concentration in the Earth's crust obtained through the abundance in mass percentage [28]–[30] (Figure 11).

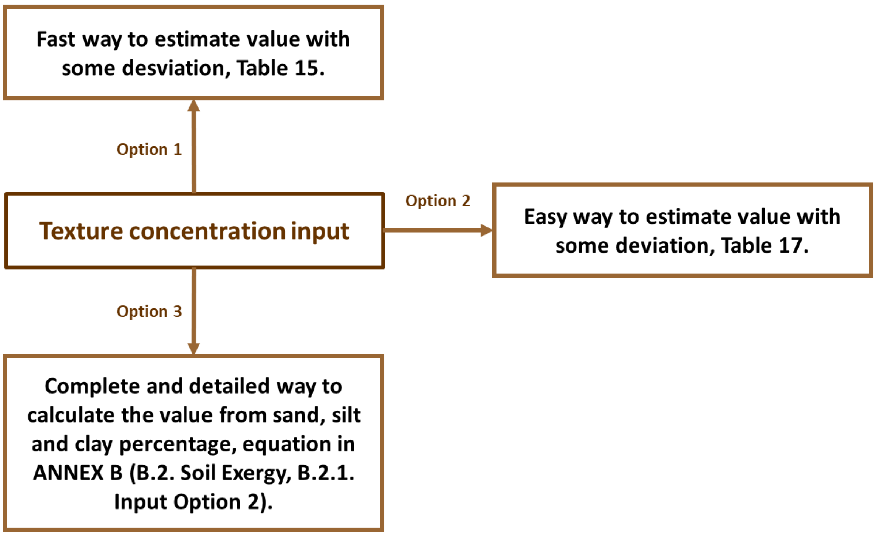

Figure 11 — Diagram explaining the method of calculating the texture concentration input based on the different possible starting data available

Table 17 — Concentration input values for texture

Texture	Average concentration input (kJ/kg)
Sand	0
Sandy loam	325,377
Loam	**492,103**
Silt loam	304,592
Silt	35,802
Sandy clay loam	145,492
Clay loam	386,576
Silty clay loam	294,325
Silty clay	260,647
Sandy clay	27,720
Clay (< 70 % clay)	30,436
Clay (> 70 % clay)	0

The values from Table 17 are established as an easy way of value approximation for texture exergy concentration. In these data, clay (> 70% clay) and sand do not have exergy due to their deficient properties and plant growth develop. The choice of these values will involve some deviation. If more realistic data is needed, formulas of section Annex B (B.2 Soil Exergy, B.2.1 Texture Input Option 2.1) can be followed for a more complete calculation of texture concentration input.

The exergy of soil is also due to the nutrient's concentration (Figure 12). The complete methodology for the calculation is developed in section Annex B (B.2 Soil Exergy, B.2.2 Nutrients Input Option 2.2). The calculation is performed considering that a high level of nutrients are present in an agricultural soil, obtaining the value given in Table 15. This value shall be directly used assuming a possible deviation. If a value that takes into account all the nutrient data in the real situation needs to be calculated, the formulas included in Annex B (B.2 Soil Exergy, B.2.2 Nutrients Input Option 2.2) should be used.

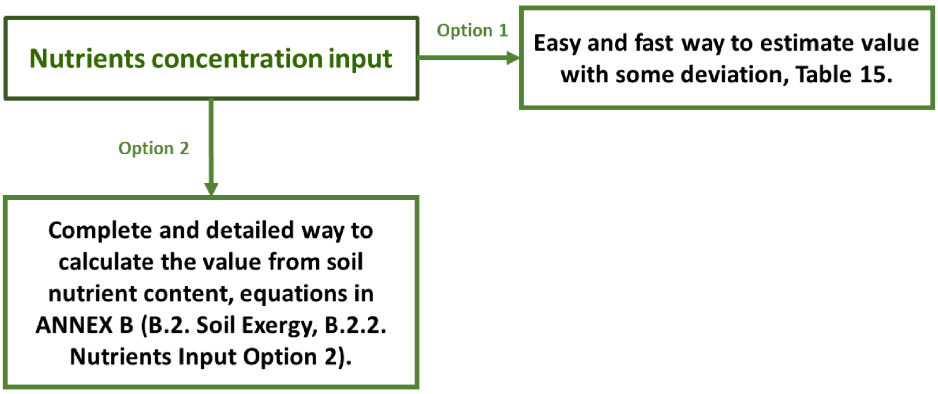

Figure 12 — Diagram explaining the method of calculating the nutrients concentration input based on the different possible starting data available

If organic matter data is not available and a quicker and simpler approximation is desired, the data in Table 15 shall be used. It should be noted that this value will have a deviation associated with it. If organic matter content data is available, Formula 23 shall be used (Figure 13).

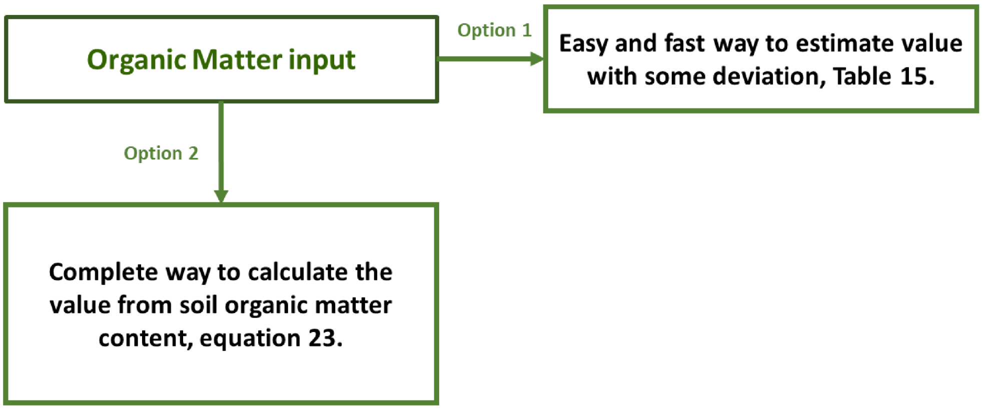

Figure 13 — Diagram explaining the method of calculating organic matter input based on the different possible starting data available

$$Organic\ Matter\ Input\left(kJ\ /\ kg\right) = 19\,406{,}12kJ\ /\ kg \cdot \frac{Organic\ matter\ content\left(\%\right)}{100} \qquad (23)$$

The last part that constitutes the input of the soil is the microorganisms. The input of the microorganisms shall be based on total soil DNA data obtained from ISO 11063:2020 analysis [36]–[39]. If complete DNA data are not available and a quicker and simpler approximation is desired, the data in Table 15 shall be used. It should be noted that this value will have a deviation associated with it. If soil DNA data are available, the formulas in section Annex B, B.2. Soil Exergy, B.2.3. Microorganisms Input Option 2.4 shall be used (Figure 14).

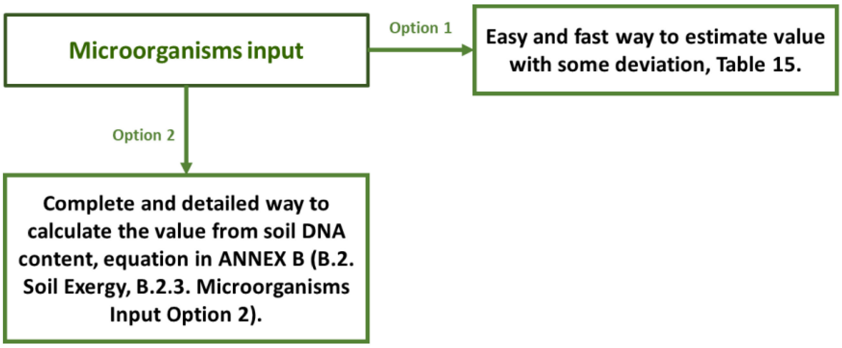

Figure 14 — Diagram explaining the method of calculating the microorganisms input based on the different possible starting data available

4.3.2.6.3 Erosion soil losses exergy

Soil losses due to erosion will be estimated by considering the soil exergy and the amount of soil lost (Formula 24):

$$Soil\ losses\left(\frac{MJ}{ha\cdot year}\right) = Factor\ A\left(\frac{t}{ha\cdot year}\right)\cdot Soil\ exergy\left(\frac{kJ}{kg}\right) \qquad (24)$$

4.4 Parameter unification

The information and values obtained for each parameter will be recapitulated. This unification is necessary in any case study. By unifying the subfactors, the global computation of each can be analysed, and this allows the magnitude of the values obtained to be observed in greater detail. In this way, the importance of each activity and process carried out on the soil can be evaluated.

In this way, it can be seen how the methodology developed allows:

— Use of Amendment Subfactors and Erosion Soil Losses as Impacts on Soil (S) to assess soil degradation.

— Study of the agricultural process and evaluation of different fertilisation treatments through Crop Exergy Footprint (CEF).

— Apply only one indicator, exergy, for assess all the agricultural process and soil system as a whole.

Annex A

(informative)

Example of use of the methodology

A.1 General

An example of how the defined methodology should be used within an agricultural process is developed. The methodology is applied to a wheat production process.

A reference level of maximum fertility should be selected for the calculations. This reference level is established based on optimal amount of each property from literature references and agronomic knowledge. It is a level established at a theoretical level to be able to carry out the assessment. This level does not show the real fertile soil because there is a wide range of fertile soils in the world.

The initial soil analyses of the wheat crop should be considered (Table A.1). For the final soil condition, the analyses of the conventional treatments should be used. These data will be necessary to be able to analyse the variation of the different factors selected as Impacts on soil (IoS).

Table A.1 — Initial analysis of the starting soil and final analysis of the conventional treatment of the wheat

Soil	Unit	Maximum value considered	Initial	Final	Suggested method
pH	**—**	**7,00**	8,0	6,50	EN ISO 10390:2022
Conductivity	**dS/M**		0,285	0,25	ISO 11265:1994
N total	**%**	**0,30**	0,245	0,25	ISO 11261:1995
N organic	**g/100 g**	**0,17**	0,20	0,19	—
N inorganic	**mg/kg**	**1 265,0**	480,20	440,00	—
Organic matter	**%**	**3,70**	4,2	3,5	EN 13039:2011
Organic carbon	**%**	**2,0**	2,43	2,30	ISO 10694:1995
Rate C/N	**—**		9,9	9,34	—
P	**mg/kg**	**25,0**	98,7	44,71	EN 11263:1994
K	**mg/kg**	**250,0**	485,2	604,47	ISO 9964-2:1993
Ca	**mg/kg**	**4 000,0**	4401	4 401,52	EN 16171:2016
Mg	**mg/kg**	**300,0**	240,4	287,27	EN 16171:2016
Total carbonates	**%**		26,9	35,97	—
Active limestone	**%**		11,9	12,23	—

Soil	Unit	Maximum value considered	Initial	Final	Suggested method
CEC	meq/100 g		26,1	26,79	EN ISO 11260:2018
Na	meq/100 g	1,00	0,94	1,60	ISO 9964-1:1993
Cu	mg/kg	2,00	2,8	3,03	ISO 11047:1998
Fe	mg/kg	2,50	14,2	8,22	EN 16171:2016
Mn	mg/kg	5,00	4,3	19,38	ISO 11047:1998
Zn	mg/kg	1,50	3,4	2,43	ISO 11047:1998
Sand	%	40,00	50,9	50,9	—
Silt	%	40,00	27,2	27,2	—
Clay	%	20,00	21,9	21,9	—
EPS (sodicity)	%	5,00	3,60	5,97	—
DNA	mg DNA/kg soil	66,62	33,18	38,33	EN ISO 11063:2020

In this annex, the agricultural process will be studied in detail. In the development of the methodology, the different activities carried out during cultivation, such as tillage, fertilization, and application of amendments, irrigation, and erosion, are included. Based on the different energy consumptions established for the activities carried out in the cultivation process, estimates and calculations will be made to obtain the exergy involved in the process.

In the case of wheat cultivation, the preparatory tasks were chisel, rolling cultivator and spring tine cultivator. Wheat was sown with a seed drill at a rate of 200 kg of seed/ha. The plot was irrigated with blanket irrigation, with a total of 3 irrigations. Basal and coverage fertilizers were applied. Basal has a composition of 0-30-0 at a rate of 95 kg/ha. Coverage has a composition of 46-0-0 with a dose of 150 kg/ha. No herbicides were applied.

A.2 Crop exergy footprint (CEF)

A.2.1 Mechanical processes

In this study, the consumption of the machinery is not provided, but only the machinery used. Therefore, the energy data can be calculated based on those provided in Table A.2 for each type of machinery.

It was considering the data provided and the fact that the soil texture as sandy clay loam texture (heavy texture), it was selected as the soil to be used for tillage operations.

In the case of tillage operations, high depth and heavy texture are selected for chisel, rolling cultivator, and spring tine cultivator. The machinery for sowing processes, the single seed drill with a normal implement width is selected. The cereal harvester with a normal working capacity is selected for the consumption of the machinery resulting in Table A.2.

Table A.2 — Energy consumption of tillage processes and sowing and harvesting machinery

WHEAT		(MJ/ha)
Tillage		
	Chisel plow	687,01
	Rolling cultivator	763,34
	Spring tine cultivator	305,34
Seed drill		
	Single seed drill	267,17
Harvester		
	Cereal harvester	343,50
TOTAL (MJ/ha)		**2 366,37**

A.2.2 Water

The type of crop and irrigation is provided but not the amount of water used the data provided in Table 7 for water consumption according to crop and A.3 for energy consumption according to the type of irrigation should be used.

Wheat is an herbaceous crop, and as it is blanket irrigation, the consumption corresponding to a low irrigation zone (0,04 kWh/m^3) and gravity irrigation (consumption per irrigation 4,778 m^3/ha) is considered (Table A.3).

Table A.3 — Energy consumption of the irrigation process

Water		
	Blanket (every 20-25 days) kWh/ha	191,14
	3 irrigations kWh/ha	573,42
TOTAL (MJ/ha)		**2 064,30**

A.2.3 Fertilization

Regarding the agricultural process, the fertilization that is studied, both for basal and coverage dressing. Knowing the composition of the fertilizers in nitrogen, phosphorus, and potassium, the consumption for obtaining these fertilizers is calculated from the costs established for each nutrient in Table 3 and the consumption of normal centrifugal spreader machinery (Table 2) resulting in (Table A.4).

Table A.4 — Energy consumption of the fertilization process for conventional treatment

Basal dressing		
	0-30-0 (kg P)	12,39
	95 kg/ha	665,42
Coverage dressing		
	urea (46-0-0) (kg N)	69,00
	150 kg/ha	4 514,65
TOTAL (MJ/ha)		**5 180,07**

A.2.4 Total CEF1

Mechanical processes, water and fertilization, Table A.5 is obtained.

Table A.5 — Total exergy involves in the agricultural process

	Exergy (MJ/ha)
Mechanical processes	2 366,37
Water	2 064,30
Fertilization	5 180,07
CEF_1 (MJ/ha)	**9 610,74**

A.2.5 Diffuse emission pool

The diffuse emissions generated due to the application of fertiliser to the field calculated following the formulas shown in 4.3.1.4. *Diffuse emissions* are summarised in Table A.6:

Table A.6 — Emissions are derived from the soil system

Fertilizer	Pollutant	Emissions generated
Basal: NPK (0-30-0) 95 kg/ha + Coverage: Urea (46-0-0) 150 kg/ha	NH_3 (kg/ha·year)	10,35
	P_2O_5 (kg/ha·year)	0,25
	N_2O (Kg N_2O/ha·year)	1,22
	NO_x is (kg NO_x/ha·year)	0,26

The emissions generated are proportional to the units of nitrogen and phosphorus used in fertilization.

A.2.6 CEF in terms of production

In this example, the wheat yield obtained is 82 700 kg/ha. Then, the above table are obtained with respect to kg of crop (Table A.7).

Table A.7 — Factors in terms of production

	CEF_1
Exergy	9 610,74 MJ/ha
Exergy in units of production	0,116 MJ/kg crop

A.3 Impacts on soil (IoS)

The parameters are evaluated to see whether they have been influenced positively or negatively after the agricultural process. For the estimation of the variation of the parameters, the defined optimum state, is also included (A.2.3.2. Soil exergy). In this way, if the soil has suffered a decrease in the concentration of a parameter, it will only be restored to the optimum concentration if the initial state was higher than the optimum. Conversely, if the concentration of the parameter in the initial state is lower than the optimum, the exergy cost necessary to recover the concentration of the parameter will be applied only up to the initial state and not up to the optimum (Table A.8).

Table A.8 — Variation of the parameters in the final state with respect to the initial state of the soil

	Variation	
OM	-0,20	%
N	-40,20	mg/kg
P	19,71	mg/kg
K	354,47	mg/kg
Ca	401,52	mg/kg
Mg	46,87	mg/kg
Na	0,66	meq/100 g
Cu	1,03	mg/kg
Fe	5,72	mg/kg
Mn	15,08	mg/kg
Zn	0,93	mg/kg
EPS	-2,37	%
pH	-0,50	pH
	0,50	cmolc $CaCO_3$/kg soil

A.3.1 Nutrients Amendment

The amendment of the nutrients is proportional to the energy involved in the process of generating the nitrogenous mineral fertiliser (urea), with the transport and indirect processes of its production, the production of compost and its transport. This parameter includes the energy consumption of the mechanical processes necessary for its application in the field.

In this case, the nitrogen in both the final state is below the initial state. The Nitrogen Amendment should be calculated as the amount of nitrogen needed to recover the initial state through Formula 9 and Formula 10.

$$N\left({}^{kg}\!/_{ha}\right) = \frac{40,20}{10^6}\, {}^{kg\ N}\!/_{kgsoil} \cdot 10\,000\,\frac{m^2}{ha} \cdot 0,3\ m \cdot 1\,400\,{}^{kgsoil}\!/_{m^3} = 168,84\,{}^{kg}\!/_{ha}$$

$$N\ Amendment\left(\frac{MJ}{ha}\right) = 168,84\,\frac{kg\ N}{ha} \cdot 67,8\,\frac{MJ}{kg\ N} + \frac{0,229\,\frac{MJ}{kg\ Urea} \cdot 168,84\,\frac{kg\ N}{ha}}{0,46\,\frac{kg\ N}{kg\ Urea}} = 11\,531,4\,{}^{MJ}\!/_{ha}$$

In Table A.1 is shown how the phosphorus content after the agricultural process has decreased (Initial 98,7 mgP/kg soil vs Final 44,71 mgP/kg soil). However, this decrease does not imply a Nutrient Amendment because the phosphorus concentration in the final state is still higher than the one established in optimal state (Final 44,71 mgP/kg soil > 25 mgP/kg soil).

A.3.2 Organic Matter Amendment

In this case, the organic matter in the final state is below the initial state. The Organic Matter Amendment should be calculated as the amount of organic matter needed to recover the initial state (0,2 %) through Formula 11 and Formula 12.

$$OM\left(kg/ha\right) = \frac{0,2}{100}\,kg/kg\ soil \cdot 10\,000\,\frac{m^2}{ha} \cdot 0,3m \cdot 1\,400\,kg\ soil/m^3 \cdot \frac{100}{10} = 84\,000\,kg/ha$$

$$OM\ Amendment\left(MJ/ha\right) = \frac{84\,000\,\frac{kg}{ha}\left[76\,\frac{kJ}{kg} + 229\,\frac{kJ}{kg}\right]}{1\,000\,\frac{kJ}{MJ}} = 25\,620\ MJ/ha$$

A.3.3 Salinity Amendment

The ESP in the final state is higher than the initial content and, it is higher than the set optimum limit. The amount of sodium in the soil will have to be reduced by adding gypsum. In this case, gypsum will be added until the optimum limit is reached. This is because not so much effort is needed if the concentration at the optimum level is already adequate for the soil. The Salinity Amendment should be calculated as the amount of sulphur and gypsum needed to recover the initial state through Formula 13 and Formula 14.

$$Sulphur\left(kg/ha\right) = \left(\frac{ESP_{final} - ESP_{initial}}{100}\right) \cdot CEC \cdot 873,6 = \left(\frac{5,97 - 5}{100}\right) \cdot 26,79 \cdot 873,6 = 227,02$$

$$Salinity\ Amendment\left(MJ/ha\right) = 227,02\,kg/ha \cdot 3,7\,\frac{MJ}{kg\ S} + \frac{0,229\,\frac{MJ}{kg\ comp} \cdot 227,02\,kg/ha}{0,186\,\frac{kg\ S}{kg\ compound}} = 1\,119,3\ MJ/ha$$

A.3.4 Acidification Amendment

The pH in the final state is 6.5, showing a decrease from the initial state (pH 8). The pH will have to be increased from the incorporation of limestone into the soil. In this case, limestone will be added until the optimum limit (pH 7) is reached. This is because not so much effort is needed if the concentration at the optimum level is already adequate for the soil.

The difference between the soil pH and the desired pH is extrapolated on the curve (Figure 5). The Acidification Amendment should be calculated as the amount of calcium needed to recover the initial state through Formula 16 and Formula 17.

$$Ca\left(kg/ha\right) = CaCO_3\left(cmol_c/kg\ soil\right) \cdot 1\,638 = 0,5\,cmol_c/kg\ soil \cdot 1\,638 = 819$$

$$Acidification\ Amendment\left(MJ/ha\right) = 819\,\frac{kg}{ha} \cdot 2,3\,\frac{MJ}{kg\ Ca} + \frac{0,229\,\frac{MJ}{kg\ comp} \cdot 819\,kg/ha}{0,39\,\frac{kg\ Ca}{kg\ compound}} = 2\,364,6\ MJ/ha$$

A.3.5 Erosion soil losses

A.3.5.1 Soil erosion

Concerning erosion losses and knowing the location of the agricultural process, together with the initial data, the erosion that the soil can suffer on an annual basis has been calculated. For this calculation, meteorological data from a nearby weather station (rainfall, factor R), texture and organic matter (factor K), type of crop and agricultural practices (factor C), length and slope of the land (factor LS), and support practices (factor P) were used.

Table A.9 — Monthly rainfall data at the meteorological station near the agricultural process site

Rainfall month (mm)	Year 2019	Year 2018	Year 2017	p_i
January	4,8	15,6	9,1	**9,83**
February	4,2	37	19,2	**20,13**
March	23,4	66	44,8	**44,73**
April	94,8	46,8	12	**51,20**
May	17,2	106,4	39,4	**54,33**
June	2	39,4	67,4	**36,27**
July	68,2	16,4	12,6	**32,40**
August	20,4	124,4	40	**61,60**
September	43,2	64,8	9,4	**39,13**
October	31	146,4	11,8	**63,07**
November	30,4	36	5,8	**24,07**
December	30,4	8,6	15	**18,00**
TOTAL	370	707,8	286,5	**454,77 (P)**

Considering the data from the meteorological station (Table A.9), it is calculated p_i and P is calculated as the average of the month considering the values of all years and the mean of the total of each year, respectively. MFI should be calculated from -Formula B.3 , obtaining a value of 45,40 mm:

$$MFI = \frac{\sum_{i=1}^{12} p_i^2}{P} = 45,40\ mm$$

MFI is less than 55 mm, so formula B.1 is used to calculate the R-factor.

$$R = 0.7399 \cdot MFI^{1.847} = 0.7339 \cdot \left(45,40\right)^{1.847} = 850,57 \frac{mm}{h \cdot ha \cdot year}$$

Depending on the type of texture, clay, and silt content, together with the organic matter, the value of particle size factor (M) is estimated (Formula B.5). In the case of not having a very fine sand fraction, assume that its value is 0. The soil structure and permeability class can also be determined (Table 10 and Table 11). In this case, soil structure (s) and permeability (p) class are 3 and 4, respectively.

$$M = \left(m_{silt} + m_{vfs}\right)\cdot\left(100 - m_c\right) = 27,2\cdot\left(100 - 21,9\right) = 2\,124,32$$

In this way, factor K is calculated following the Formula B.4:

$$K = \left[\frac{2.1\cdot10^{-4}\cdot M^{1.14}\cdot\left(12 - OM\right) + 3.25\cdot\left(s - 2\right) + 2.5\cdot\left(p - 3\right)}{100}\right]\cdot0.1317$$

$$K = \left[\frac{2.1\cdot10^{-4}\cdot\left(2\,124,32\right)^{1.14}\cdot\left(12 - 4,2\right) + 3.25\cdot\left(3 - 2\right) + 2.5\cdot\left(4 - 3\right)}{100}\right]\cdot0.1317 = 0,16\frac{t\cdot h}{MJ\cdot mm}$$

In this case, neither slope nor inclination data are available, so a value of 1 is assumed for the LS factor, which is the value of the unit plot defined for this factor, assuming a length of 22,13 m and an inclination of 9 %.

For this study, the crop is wheat (C_{crop} = 0,2), and the plowing, as mentioned above, is conventional plowing ($C_{tillage}$ = 1) with no mulching or residue practices ($C_{residues}$ = 1; C_{cover} = 1). No supporting practices have been carried out either. P factor will be 1, and the C factor will be given by Formula B.10:

$$C_{arable} = C_{crop}\cdot C_{management}$$

$$C_{management} = C_{tillage}\cdot C_{residues}\cdot C_{cover} = 1$$

$$C_{arable} = 0,2\cdot1 = 0,2$$

The amount of soil likely to be lost to erosion is estimated as 27,08 t/ha·year (Table A.10).

Table A.10 — Value of factor A, average soil loss per unit hectare in one year (t/ha-year)

	R Factor (MJ mm/h·ha·year)	K Factor (t·h/MJ mm)	LS Factor	C Factor	P Factor	A Factor (t/ha·year)
Soil understudy	850,57	0,16	1	0,2	1	**27,08**

A.3.5.2 Soil exergy

To establish the exergy value of the soils, the parameters texture (physical properties), nutrients (chemical properties), microorganisms (biological properties), and organic matter (acts as a link between all the properties) are used.

The initial exergy value has been established for the soil in order to quantify the fertility and quality of the soil used for each type of crop.

Option 1.1: Data form Table 15 is used as an easy and simple way to calculate the soil exergy.

Soil Exergy = Texture input + Nutrients input + Organic matter input + Microorganisms input

Soil Exergy = 95,26 + 492,10 + 1626,37 + 718,03 + 2 251,1 = 5 182,86 kJ/kg

Option 2.1.1: The percentage of sand, silt, and clay (50,9 %, 27,2 %, 21,9 %, respectively) should be used to calculate both chemical input ($Ex_{ch,texture}$) and concentration input ($Ex_{c,texture}$) of the texture. It should be noted that the optimal level will act as maximum fertility and therefore maximum energy value. The proportion of clay, silt or sand exceeding the percentage defined for the texture as optimal (40 %, 40 %, 20 % of sand, silt and clay) will not contribute to the exergy value of the soil under study.

$$Ex_{ch,texture2}\left(kJ/kg\right)=\left[\frac{\%\cdot 47,32kJ/kg}{100}\right]_{sand}+\left[\frac{\%\cdot 107,67kJ/kg}{100}\right]_{silt}+\left[\frac{\%\cdot 166,33kJ/kg}{100}\right]_{clay}$$

$$Ex_{ch,texture}\left(kJ/kg\right)=\left[\frac{40\cdot 47,32kJ/kg}{100}\right]_{sand}+\left[\frac{27,2\cdot 107,67kJ/kg}{100}\right]_{silt}+\left[\frac{20\cdot 166,33kJ/kg}{100}\right]_{clay}=81,48\ kJ/kg$$

The concentration input of the texture is calculated in two ways. Option 2.1.2: easy and fast way to estimate value with some deviation with data from Table 16, and Option 2.1.3: complete and detailed way to calculate the value from sand, silt and clay percentage, formulas in Annex B (B.2 Soil Exergy, B.2.1 Texture Input Option 2.1).

<u>*Option 2.1.2*</u> (Table 16): Texture of soil under study is sandy clay loam.

$$Ex_{c,\ texture2}=145,492\ kJ/kg$$

The values established as optimal will act at maximum. If the content of sand, silt or clay is higher than the optimum, 40 %, 40 % and 20 % respectively, the value of the optimum will be taken for the calculation.

<u>*Option 2.1.3*</u>:

$$Ex_{c,\ texture3}=Ex_{c,q}+Ex_{c,ps}+Ex_{c,os}+Ex_{c,ss}$$

$$x_{m,q}=\left[\frac{40\cdot 0,77}{100}\right]_{sand}+\left[\frac{27,2\cdot 0,59}{100}\right]_{silt}+\left[\frac{20\cdot 0,168}{100}\right]_{clay}=0,502$$

$$Ex_{c,\ q}=41,252\cdot\left(2,35+\ln\left(0,589\right)+\frac{\left(1-0,589\right)}{0,589}\cdot\ln\left(1-0,589\right)\right)=39,992$$

$$x_{m,ps}=\left[\frac{40\cdot 0,178}{100}\right]_{sand}+\left[\frac{27,2\cdot 0,142}{100}\right]_{silt}+\left[\frac{21,9\cdot 0,009}{100}\right]_{clay}=0,112$$

$$Ex_{c,ps}=147,21\cdot\left(1,765+\ln\left(x_{m,ps}\right)+\frac{\left(1-x_{m,ps}\right)}{x_{m,ps}}\cdot\ln\left(1-x_{m,ps}\right)\right)=-201,62$$

$$x_{m,os}=\left[\frac{40\cdot 0,052}{100}\right]_{sand}+\left[\frac{27,2\cdot 0,198}{100}\right]_{silt}+\left[\frac{21,9\cdot 0,198}{100}\right]_{clay}=0,114$$

$$Ex_{c,os}=394,414\cdot\left(4,434+\ln\left(x_{m,os}\right)+\frac{\left(1-x_{m,os}\right)}{x_{m,os}}\cdot\ln\left(1-x_{m,os}\right)\right)=-13,932$$

$$x_{m,ss} = \left[\frac{27,2 \cdot 0,07}{100}\right]_{silt} + \left[\frac{21,9 \cdot 0,625}{100}\right]_{clay} = 0,114$$

$$Ex_{c,ss} = 107,238 \cdot \left(2,732 + \ln\left(x_{m,ss}\right) + \frac{\left(1 - x_{m,ss}\right)}{x_{m,ss}} \cdot \ln\left(1 - x_{m,ss}\right)\right) = -13,932$$

$$Ex_{c,texture3} = 346,694\ kJ / kg$$

The values of each option have a deviation of 57,8 %. This deviation is expected to have if the option easy is selected instead of option 2.1.2 in the case of the soil under study.

The concentration input of the nutrients is calculated in two ways. Option 1: easy and fast way to estimate value with some deviation with data from Table 17, and Option 2: complete and detailed way to calculate the value from nutrient soil content, formulas in Annex B (B.2 Soil Exergy, B.2.2 Nutrients Input Option 2).

Option 1.2 (Table 15):

$$Ex_{c,\ nutrient1} = 1\,626,37\ kJ / kg$$

The values established as optimal will act at maximum. If the content of nutrients is higher than the optimum, the value of the optimum will be taken for the calculation (Table A.1).

Option 2.2:

$$Ex_{c,\ nutrient2} = 1\,545,55\ kJ / kg$$

The values of each option have a deviation of 3,8 %. This deviation is expected to have if the option easy is selected instead of option 2 in the case of the soil under study.

In the soil analyses shown above, the percentage of organic matter and organic carbon in the soil can be observed.

Option 1.3 (Table 15):

$$Ex_{c,OM1}\left({}^{kJ}\!/_{kg}\right) = 1\,9406,12\ {}^{kJ}\!/_{kg} \cdot \frac{3,7}{100} = 718,03\ {}^{kJ}\!/_{kg}$$

Option 2.3: Specifically, for the soil in the initial state, the organic carbon content is 2,43 % obtained from calcination.

$$Organic\ Matter\left(\%\right) = Organic\ Carbon\left(\%\right) \cdot \frac{100}{54}$$

$$Organic\ Matter\left(\%\right) = 2,43\ \% \cdot \frac{100}{54} = 4,5\ \%$$

$$Ex_{c,OM}\left({}^{kJ}\!/_{kg}\right) = 19\,406,12\ {}^{kJ}\!/_{kg} \cdot OM\left(\%\right) / 100$$

The established reference state of maximum fertility has an optimum value of OM above which an increase does not imply an increase in the quality and fertility of the soil. In this reference state, 2 % organic carbon, or 3,7 % organic matter, has been selected. The organic matter in the example is higher than the optimum, so the OM energy will be calculated from the percentage set.

$$Ex_{c,OM2}\left({kJ}/{kg}\right) = 19\,406,12\,{kJ}/{kg} \cdot \frac{3,7}{100} = 718,03\,{kJ}/{kg}$$

The last parameter established for the determination of soil exergy is the biological property of microorganisms. The content in the initial state of DNA is 33,18 mg/kg soil.

Option 1.4 (Table 15):

$$EcoEx_1 = 2251,10\ kJ\ /\ kg$$

Option 2.4:

$$EcoexergyEx_2 = 19\,406,12\,{kJ}/{kg} \cdot 39.17 \cdot 4,45 \cdot 10^{-5} \cdot 33,18\,{mg}/{kg\ soil} = 1\,122,35$$

The values of each option have a deviation of 47,3 %. This deviation is expected to have if the option easy is selected instead of option 2.4 in the case of the soil under study.

The exergy of the soil in the initial state is shown in the Table A.11.

Table A.11 — Total exergy of initial soil

	Exergy (kJ/kg) Option 1	Exergy (kJ/kg) Option 2	Exergy (kJ/kg) Option 2 and Texture Concentration input as Option 3
Texture	95,26+492,10	81,48+145,49	81,48+346,69
Nutrients	1 626,37	1 545,55	1 545,55
Organic matter	718,03	718,03	718,03
Microorganisms	2 251,10	1 121,08	1 121,08
Total	**5 182,86**	**3 611,63**	**3 812,83**

A.3.5.3 Erosion soil losses exergy

The Soil losses in the initial state are shown in the Table A.12.

$$Soil\ losses\left(\frac{MJ}{ha \cdot year}\right) = Factor\ A\left(\frac{t}{ha \cdot year}\right) \cdot Soil\ exergy\left(\frac{kJ}{kg}\right)$$

Table A.12 — Total Erosion as the term Soil losses

Soil losses Option 1 (MJ/ha·year)	Soil losses Option 2 (MJ/ha·year)	Soil losses Option 2 and Texture Concentration input as Option 3 (MJ/ha·year)
140 351,85	97 802,94	103 251,44

The standard deviation between options is 20,3 %. The conservative option (option 1) is the one with the greatest erosion loss value.

A.3.6 Total IoS

All the data obtained for each factor are combined to obtain the total Impacts on soil (IoS_1, Table A.13).

Table A.13 — Total Impacts on Soil needed

	(MJ/ha)
Nutrients	11 531,4
Organic Matter	25 620
Salinity	1 119,3
Acidification	2 364,6
IoS (MJ/ha)	**40 635,30**

The wheat yield obtained is 82 700 kg/ha. The above table are obtained with respect to kg of crop (Table A.14).

Table A.14 — Total Impacts on Soil needed based on crop production

	(MJ/kg crop)
Nutrients	0,14
Organic Matter	0,31
Salinity	0,01
Acidification	0,03
IoS (MJ/kg crop)	**0,49**

The total Impacts on soil (IoS_2) is calculated in the (Table A.15).

Table A.15 — Total Impacts on Soil needed

	MJ/ha·year	**MJ/kg crop·year**
Erosion soil losses Option 1	140 351,85	1,70
Erosion soil losses Option 2	97 802,94	1,18
Erosion soil losses Option 3	103 251,44	1,25

A.4 Parameter unification

The information and values obtained for each parameter will be recapitulated in the Table A.16.

Table A.16 — Parameter unification

CEF	**9 610,74 MJ/ha**	**0,116 MJ/kg crop**
IoS1	40 635,30 MJ/ha	0,49 MJ/kg crop
IoS2 Option 3	103 251,44 MJ/ha·year	1,25 MJ/kg crop·year

The above table shows how erosion is the process of greatest magnitude, showing the importance of this process in the loss of soil quality. IoS is higher than the CEF. This indicates the importance of the impact of the agricultural process on soil condition.

Annex B

(informative)

Supplementary information

B.1 Soil Erosión: RUSLE-USLE

$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$

As explained in 4.3.2.3.1, each factor from Formula 19 depends on the characteristics of the soil being studied in each case and its geographic location, and the type of agricultural processes applied to it.

The R factor represents the influence of rainfall and depends on the intensity of rainfall to estimate the energy per unit of rainfall [40]. The method proposed by [41], based on the average monthly rainfall of each location should be calculated through Formula B.1 or Formula B.2.

$$R = 0{,}7399 \cdot MFI^{1.847}, \quad MFI < 55\ mm \tag{B.1}$$

$$R = 95.77 - 6.081 \cdot MFI + 0.4770 \cdot MFI^{2}, \quad MFI > 55\ mm \tag{B.2}$$

Where MFI (Modified Fournier Index, mm) is defined by Arnoldus (1977) as:

$$MFI = \frac{\sum_{i=1}^{12} p_i^2}{P} \tag{B.3}$$

where

p_i is the mean monthly precipitation (mm);

P is the mean annual precipitation (mm).

The K factor represents soil erodibility, i.e., it is a global parameter that represents a value expressing the reaction of the soil profile to the process of soil detachment and loss by rainfall and surface flow [42]. The factor calculation is based on the relationship between "classical" soil properties and soil erodibility, establishing the following relationship [26], [40], [42] (Formula B.1 and B.2).

$$K = \left[\frac{2.1 \cdot 10^{-4} \cdot M^{1.14} \cdot \left(12 - OM\right) + 3.25 \cdot \left(s - 2\right) + 2.5 \cdot \left(p - 3\right)}{100} \right] \cdot 0.1317 \tag{B.4}$$

$$M = \left(m_{silt} + m_{vfs}\right) \cdot \left(100 - m_c\right) \tag{B.5}$$

where

M is the particle size factor;

m_{silt} is the percentage of silt in the soil texture (0,002-0,05 mm) (%);

m_c is the percentage of clay (< 0,002 mm) (%);

m_{vfs} is the content of the very fine sand fraction (0,05-0,1mm) (%);

OM is the organic matter content in the soil (%);

s is the soil structure class (Table B.1);

p is the permeability class (Table B.2).

Table B.1 — Classification of the different classes of soil structures derived from the European Soil Data Base

Structure	S	European Soil Database
Very fine granular (1-2 mm)	1	G (good)
Fine granular (2-5 mm)	2	N (normal)
Medium or coarse granular (5-10 mm)	3	P (poor)
Massive or in blocks (>10 mm)	4	H (humic or peat topsoil)

Table B.2 — Classification of the different permeability classes and ranges of saturated hydraulic conductivity estimated from the main soil texture classes

Texture	P	Saturated hydraulic conductivity (mm/h)
Clay, clay loam	6 (very slow)	< 1
Sandy clay loam, silty clay loam	5 (slow)	1,0-2,0
Sandy clay loam, clay loam, clay loam	4 (moderately slow)	2,0-5,1
Silty loam, loam	3 (moderate)	5,1-20,3
Silty sand, sandy loam	2 (moderately fast)	20,3-61,0
Sand	1 (fast and very fast)	> 61,0

The L and S factors are two factors where the global topography is involved. The L factor represents the length, and the S factor represents the slope. The slope length (LS) factor depends on the slope percentage and slope length and is defined as a ratio between the soil loss under given conditions and that of a site with a "standard" slope of 9 % and a slope length of 22,13 m (Formula B.6). The steeper and more prolonged the slope, the higher the erosion risk [26], [43].

$$L = \left(\frac{\lambda}{22,13} \right)^m \qquad \text{(B.6)}$$

where

L is the slope length factor;

λ is the slope length (m);

22,13 is the length of the defined unit plot;

m is the slope length exponent.

The slope length exponent "m" determines the relationship between in-furrow erosion (caused by flow) and inter-furrow erosion (caused by raindrop impact). In Formula B.7, θ is the slope angle (degrees).

$$m = 0,1342 \times ln\theta + 0,192 \quad \text{(B.7)}$$

The factor S representing the slope can be estimated from Formula B.8 or B.9 [26], [43].

$$S = 10,8 \cdot \sin\theta + 0,03 \quad pendiente < 9\ \% \quad \text{(B.8)}$$

$$S = 16,8 \cdot \sin\theta - 0,05 \quad pendiente \geq 9\ \%) \quad \text{(B.9)}$$

where

S is the slope steepness factor;

θ is the slope angle (degrees).

The influence of land use and management equation is represented by factor C. This factor represents the conditions that can be most easily influenced and, the most important land-use policies and decisions [44].

The C factor based on the best available data at the European level and for proposed croplands (Formula B.10):

$$C_{arable} = C_{crop} \cdot C_{management} \quad \text{(B.10)}$$

The C_{crop} is the factor due to crop type, and $C_{management}$ quantifies the influence of cultivation practices (plowing, presence of cover crop, presence of crop residues) on the reduction of soil erosion. Other practices such as contour farming, terraces, or strip cropping are considered within the supporting practices factor (P factor). The Table B.3 shows the different values defined for the C_{rop} factor according to crop type [44].

Table B.3 —Defined values of the C_{rop} factor according to the type of crop

Type of crop	C-crop factor
Common wheat and spelt	0,2
Durum wheat	0,2
Rye	0,2
Barley	0,21
Corn-corn grain	0,38
Rice	0,15
Dried pulses and protein crops	0,32
Potatoes	0,34
Beets	0,34
Oilseeds	0,28
Rapeseed and turnip rape	0,3
Sunflower seed	0,32
Linseed	0,25
Soybeans	0,28
Cottonseed	0,5
Tobacco	0,49
Fallow	0,5

The combined effect of plowing ($C_{tillage}$), residue maintenance ($C_{residues}$), and cover crop maintenance (C_{over}) are considered for the estimation of $C_{Management}$ (Formula B.8):

$$C_{management} = C_{tillage} \times C_{residues} \times C_{cover} \qquad \text{(B.11)}$$

where

$$C_{tillage} = F_{conventional} \times 1 \times F_{conservation} \times 0,35 \times F_{notill} \times 0,25 \qquad \text{(B.12)}$$

$F_{conventional}$ is the percentage of soil with conventional treatment;

$F_{conservation}$ is the percentage of soil with conservation treatment;

F_{notill} is the percentage of soil without plowing.

$$C_{residues} = 1 \times (0,88 \times F_{residues}) + \left(1 - F_{residues}\right) \qquad \text{(B.13)}$$

$F_{residues}$ is the percentage of soil with residue treatment.

$$C_{cover} = 1 \times (0,80 \times F_{crop-cover}) + \left(1 - F_{crop-cover}\right) \qquad \text{(B.14)}$$

$F_{crop\text{-}cover}$ is the percentage of soil with cover.

In this methodology, the values assumed provided by [45], should be used:

— $C_{tillage}$ = 1 conventional plough.

— $C_{tillage}$ = 0,35 conservation plough.

— $C_{tillage}$ = 0,25 no plough.

The calculation and estimation of soil erosion also include the P factor. The P factor is defined as conservation or support practices and is the ratio of soil loss between a plot where mechanical soil conservation practices (contours, terraces, strip cropping, etc.) are applied for erosion control and the losses that occur on a plot if such practices are not applied, and tillage is done in the direction of the slope. When no or very few conservation practices are applied, the value of P is equal to 1. If, reverse slope terraces are used, the value of the P factor is equal to 0,2. The Table B.4 shows the values that should be used for the different usual conservation practices [26].

Table B.4 — Defined values for the P-factor for conservation practices according to different field applications

Slope (%)	Contour factor	Stripcrop factor	Computing sediment yield	
			Graded channels sod outlets	Steep backslope underground outlets
1-2	0,60	0,3	0,12	0,05
3-8	0,50	0,25	0,1	0,05
9-12	0,60	0,3	0,12	0,05
13-16	0,70	0,35	0,14	0,05
17-20	0,80	0,4	0,16	0,06
21-25	0,90	0,45	0,18	0,06

B.2 Soil Exergy

B.2.1 Texture Input Option 2.1

It should be calculated the mass fraction for quartz (x_q), primary silicate minerals (x_{ps}), other secondary silicate minerals (x_{os}) and secondary silicate minerals (x_{ss}) (Formulas B.17, B.19, B.21 and B.23, respectively) for estimate the Input for each mineral: quartz ($Ex_{c,q}$), primary silicate minerals ($Ex_{c,ps}$), other secondary silicate minerals ($Ex_{c,os}$) and secondary silicate minerals ($Ex_{c,ss}$) (Formulas B.16, B.18, B.20 and B.22, respectively). Texture input should be the summatory of all mineral inputs (Formula B.15).

$$Ex_{c,\,texture} = Ex_{c,q} + Ex_{c,ps} + Ex_{c,os} + Ex_{c,ss} \tag{B.15}$$

$$Ex_{c,\,q} = 41{,}252 \cdot \left(2{,}35 + \ln\left(x_{m,q}\right) + \frac{\left(1 - x_{m,q}\right)}{x_{m,q}} \cdot \ln\left(1 - x_{m,q}\right) \right) \tag{B.16}$$

$$x_{m,q} = \left[\frac{\%\cdot 0,77}{100}\right]_{sand} + \left[\frac{\%\cdot 0,59}{100}\right]_{silt} + \left[\frac{\%\cdot 0,168}{100}\right]_{clay} \quad (B.17)$$

$$Ex_{c,ps} = 147,21\cdot\left(1,765 + \ln\left(x_{m,ps}\right) + \frac{\left(1 - x_{m,ps}\right)}{x_{m,ps}}\cdot\ln\left(1 - x_{m,ps}\right)\right) \quad (B.18)$$

$$x_{m,ps} = \left[\frac{\%\cdot 0,178}{100}\right]_{sand} + \left[\frac{\%\cdot 0,142}{100}\right]_{silt} + \left[\frac{\%\cdot 0,009}{100}\right]_{clay} \quad (B.19)$$

$$Ex_{c,os} = 394,414\cdot\left(4,434 + \ln\left(x_{m,os}\right) + \frac{\left(1 - x_{m,os}\right)}{x_{m,os}}\cdot\ln\left(1 - x_{m,os}\right)\right) \quad (B.20)$$

$$x_{m,os} = \left[\frac{\%\cdot 0,052}{100}\right]_{sand} + \left[\frac{\%\cdot 0,198}{100}\right]_{silt} + \left[\frac{\%\cdot 0,198}{100}\right]_{clay} \quad (B.21)$$

$$Ex_{c,ss} = 107,238\cdot\left(2,732 + \ln\left(x_{m,ss}\right) + \frac{\left(1 - x_{m,ss}\right)}{x_{m,ss}}\cdot\ln\left(1 - x_{m,ss}\right)\right) \quad (B.22)$$

$$x_{m,ss} = \left[\frac{\%\cdot 0,07}{100}\right]_{silt} + \left[\frac{\%\cdot 0,625}{100}\right]_{clay} \quad (B.23)$$

B.2.2 Nutrients Input Option 2.2

It should be calculated the Input for each nutrient: nitrogen ($Ex_{c,N}$), phosphorus ($Ex_{c,P}$), potassium ($Ex_{c,K}$), calcium ($Ex_{c,Ca}$), magnesium ($Ex_{c,Mg}$), sodium ($Ex_{c,Na}$), cupper ($Ex_{c,Cu}$), iron ($Ex_{c,Fe}$), manganese ($Ex_{c,Mn}$) and zinc ($Ex_{c,Zn}$) (Formulas B.24, B.25, B.26, B.27, B.28, B.29, B.30, B.31, B.32, B.33 respectively). The mass fraction for each nutrient ($x_{m,i}$) should be calculated from soil analysis.

$$Ex_{c,\,N}\left(kJ / kg\right) = 39,979\cdot\left(18,322 + \ln\left(x_{m,N}\right) + \frac{\left(1 - x_{m,N}\right)}{x_{m,N}}\cdot\ln\left(1 - x_{m,N}\right)\right) \quad (B.24)$$

$$Ex_{c,\,P}\left(kJ / kg\right) = 26,101\cdot\left(16,477 + \ln\left(x_{m,P}\right) + \frac{\left(1 - x_{m,P}\right)}{x_{m,P}}\cdot\ln\left(1 - x_{m,P}\right)\right) \quad (B.25)$$

$$Ex_{c,\,K}\left(kJ / kg\right) = 63,4\cdot\left(8,826 + \ln\left(x_{m,K}\right) + \frac{\left(1 - x_{m,K}\right)}{x_{m,K}}\cdot\ln\left(1 - x_{m,K}\right)\right) \quad (B.26)$$

$$Ex_{c,\,Ca}\left(kJ / kg\right) = 61,862\cdot\left(8,787 + \ln\left(x_{m,Ca}\right) + \frac{\left(1 - x_{m,Ca}\right)}{x_{m,Ca}}\cdot\ln\left(1 - x_{m,Ca}\right)\right) \quad (B.27)$$

$$Ex_{c,\ Mg}\left(kJ\ /\ kg\right) = 101{,}988\cdot\left(7{,}60 + \ln\left(x_{m,Mg}\right) + \frac{\left(1 - x_{m,Mg}\right)}{x_{m,Mg}}\cdot\ln\left(1 - x_{m,Mg}\right)\right) \tag{B.28}$$

$$Ex_{c,\ Na}\left(kJ\ /\ kg\right) = 107{,}822\cdot\left(5{,}525 + \ln\left(x_{m,Na}\right) + \frac{\left(1 - x_{m,Na}\right)}{x_{m,Na}}\cdot\ln\left(1 - x_{m,Na}\right)\right) \tag{B.29}$$

$$Ex_{c,\ Cu}\left(kJ\ /\ kg\right) = 39{,}008\cdot\left(23{,}844 + \ln\left(x_{m,Cu}\right) + \frac{\left(1 - x_{m,Cu}\right)}{x_{m,Cu}}\cdot\ln\left(1 - x_{m,Cu}\right)\right) \tag{B.30}$$

$$Ex_{c,\ Fe}\left(kJ\ /\ kg\right) = 44{,}387\cdot\left(24{,}942 + \ln\left(x_{m,Fe}\right) + \frac{\left(1 - x_{m,Fe}\right)}{x_{m,Fe}}\cdot\ln\left(1 - x_{m,Fe}\right)\right) \tag{B.31}$$

$$Ex_{c,\ Mn}\left(kJ\ /\ kg\right) = 45{,}12\cdot\left(26{,}328 + \ln\left(x_{m,Mn}\right) + \frac{\left(1 - x_{m,Mn}\right)}{x_{m,Mn}}\cdot\ln\left(1 - x_{m,Mn}\right)\right) \tag{B.32}$$

$$Ex_{c,\ Zn}\left(kJ\ /\ kg\right) = 37{,}914\cdot\left(22{,}665 + \ln\left(x_{m,Zn}\right) + \frac{\left(1 - x_{m,Zn}\right)}{x_{m,Zn}}\cdot\ln\left(1 - x_{m,Zn}\right)\right) \tag{B.33}$$

B.2.3 Microorganisms Input Option 2.4

if data on DNA contained in the soil are available, Microorganisms Input should be calculated through the Formula B.34.

$$Microorganisms\ Input_2 = 19\,406{,}12\ {}^{kJ}\!/\!_{kg}\cdot 39.17\cdot 4{,}45\cdot 10^{-5}\cdot DNA\left({}^{mg}\!/\!_{kg\ soil}\right) \tag{B.34}$$

Bibliography

[1] Jørgensen S.E. Introduction to systems ecology, First edit. Boca Raton, Florida: CRC Press Book, 2012

[2] Boto Fidalgo J.A., Pastrana Santamarta P., Suárez de Cepeda Martínez M. Consumos energéticos en las operaciones agrícolas en España. España, 2005

[3] Amenumey S.E., Capel P.D. Fertilizer Consumption and Energy Input for 16 Crops in the United States. Nat. Resour. Res. 2014, 23 (3) pp. 299–309. DOI:10.1007/s11053-013-9226-4

[4] M. Dachraoui and A. Sombrero, "Effect of tillage systems and different rates of nitrogen fertilisation on the carbon footprint of irrigated maize in a semiarid area of Castile and Leon, Spain," Soil Tillage Res., vol. 196, no. July 2019, p. 104472, 2020, doi: 10.1016/j.still.2019.104472

[5] Erdal G., Esengün K., Erdal H., Gündüz O. Energy use and economical analysis of sugar beet production in Tokat province of Turkey. Energy. 2007, 32 (1) pp. 35–41. DOI:10.1016/j.energy.2006.01.007

[6] FAO. R. N. Roy, A. Finck, G. J. Blair, and H. L. S. Tandon, "Plant Nutrition for Food Security. A Guide for Integrated Nutrient Management.," FAO Fertil. plant. Nutr. Bull. 2006, 16. DOI:10.1017/S0014479706394537

[7] A. Kaab, M. Sharifi, H. Mobli, A. Nabavi-Pelesaraei, and K. wing Chau, "Use of optimization techniques for energy use efficiency and environmental life cycle assessment modification in sugarcane production,". Energy. 2019, 181 pp. 1298–1320. DOI:10.1016/j.energy.2019.06.002

[8] Khaledian M.R., Mailhol J.C., Ruelle P., Mubarak I., Perret S. The impacts of direct seeding into mulch on the energy balance of crop production system in the SE of France. Soil Tillage Res. 2010, 106 pp. 218–226

[9] Kirova-Yordanova Z. "Cumulative exergy consumption in fertilizers production processes," in Efficiency, cost, optimization, simulation and environmental aspects of energy systems and processes (Nancy, 8-10 juillet 1998), 1998, no. volumen I

[10] Kongshaug G. "IFA Technical Conference, Marrakech, Morocco.," in IFA Technical Conference, 1998, no. September, pp. 0–14

[11] Mohammadi A., Rafiee S., Mohtasebi S.S., Rafiee H. Energy inputs - yield relationship and cost analysis of kiwifruit production in Iran. Renew. Energy. 2010, 35 (5) pp. 1071–1075. DOI:10.1016/j.renene.2009.09.004

[12] F. Mostashari-Rad, A. Nabavi-Pelesaraei, F. Soheilifard, F. Hosseini-Fashami, and K. wing Chau, "Energy optimization and greenhouse gas emissions mitigation for agricultural and horticultural systems in Northern Iran," Energy, vol. 186, p. 115845, 2019, doi: 10.1016/j.energy.2019.07.175

[13] Šarauskisa E., Masilionytė L., Juknevičius D., Buragienė S., Kriaučiūnienė Z. Energy use efficiency, GHG emissions, and cost effectiveness of organic and sustainable fertilisation. Energy. 2019, 172 pp. 1151–1160

[14] Tian Y., Lu H., Wang J., Lin Y., Campbell D.E., Jian S. Effects of canopy and understory nitrogen addition on the structure and eco-exergy of a subtropical forest community. Ecol. Indic. 2019, 106 (March) p. 105459. DOI:10.1016/j.ecolind.2019.105459

[15] G. Valves, “Potassium fertilizers – Manufacturing process of Potassium fertilizers,” 2020

[16] E. Aguilera, G. I. Guzmán, J. Infante-amate, R. García-ruiz, A. Herrera, and I. Villa, “Embodied energy in agricultural inputs. Incorporating a historical perspective,” 2015

[17] Ramírez C.A., Worrell E. Feeding fossil fuels to the soil: An analysis of energy embedded and technological learning in the fertilizer industry. Resour. Conserv. Recycling. 2006, 46 (1) pp. 75–93. DOI:10.1016/j.resconrec.2005.06.004

[18] J. Corominas, “Agua y energía en el riego, en la época de la sostenibilidad,” Ing. del agua, vol. 17, no. 3, pp. 219–233, 2010, doi: 10.4995/ia.2010.2977

[19] Asman W.A.H., Ammonia emission in Europe: updated emission and emission variations. 1992

[20] De Willigen P. An analysis of the calculation of leaching and denitrification losses as practised in the NUTMON approach. Wageningen, The Netherlands, 2000

[21] Food and Agriculture Organization of the United Nations. Assessment of soil nutrient balance. Approaches and Methodologies, Rome, 2003

[22] Nemecek T., Schnetzer J. “Methods of assessment of direct field emissions for LCIs of agricultural production systems. Data quality guideline for ecoinvent database version 3.0.,” Agroscope Reckenholz-Tänikon Res. Stn. ART. 2011, 0 (15) p. 34

[23] IPCC. “Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero.,” https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/index.html, 2006

[24] Lützow M.V. et al. Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions - A review. Eur. J. Soil Sci. 2006, 57 (4) pp. 426–445. DOI:10.1111/j.1365-2389.2006.00809.x

[25] Weil R.R., Brady N.C. The Nature and Properties of Soils. Fifteenth, 2017

[26] Wischmeier W.H., Smith D.D. “Predicting rainfall erosion losses.,” in Agricultural Handbook 537, U. Agricultural Research Service, Ed. Washington DC, USA., 1978

[27] Renard K.G., Foster G.R., Weesies G.A., McCool D.K., Yoder D.C. “Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).,” in Agricultural Handbook, 703, U. Agricultural Research Service, Ed. Washington DC, USA, 1997

[28] A. Valero and A. Valero, Thanatia: The destiny of the Earth’s mineral resources. A thermodynamic cradle-to-cradle assessment. 2014

[29] Valero A. Exergy evolution of the mineral capital on Earth. Universidad de Zaragoza, 2008

[30] Valero A., Valero A., Domínguez A. Exergy Replacement Cost of Mineral Resources. J. Environ. Account. Manag. 2013, 1 (2) pp. 147–158. DOI:10.5890/jeam.2013.05.004

[31] Leinweber P., Schulten H.R. Composition, stability and turnover of soil organic matter: investigations by off-line pyrolysis and direct pyrolysis-mass spectrometry. J. Anal. Appl. Pyrolysis. 1995, 32 (C) pp. 91–110. DOI:10.1016/0165-2370(94)00832-L

[32] Schnitzer M., Schulten H.R. Analysis of Organic Matter in Soil Extracts and Whole Soils by Pyrolysis-Mass Spectrometry. Adv. Agron. 1995, 55 (C) pp. 167–198. DOI:10.1016/S0065-2113(08)60540-4

[33] Schulten H.R., Schnitzer M. "Chemical model structures for soil organic matter and soils.," Soil Sci., vol. 162, no. 2, pp. 115–130, 1997, doi: 0038-075X

[34] Schulten H.R., Leinweber P. New insights into organic-mineral particles: Composition, properties and models of molecular structure. Biol. Fertil. Soils. 2000, 30 (5–6) pp. 399–432. DOI:10.1007/s003740050020

[35] Kathiravale S., Yunus M.N.M., Sopian K., Samsuddin A.H., Rahman R.A. Modeling the heating value of Municipal Solid Waste. Fuel. 2003, 82 (9) pp. 1119–1125. DOI:10.1016/S0016-2361(03)00009-7

[36] Joergensen R.G., Emmerling C. Methods for evaluating human impact on soil microorganisms based on their activity, biomass, and diversity in agricultural soils. J. Plant Nutr. Soil Sci. 2006, 169 (3) pp. 295–309. DOI:10.1002/jpln.200521941

[37] Bakken L.R., Olsen R.A. Buoyant densities and dry-matter contents of microorganisms: Conversion of a measured biovolume into biomass. Appl. Environ. Microbiol. 1983, 45 (4) pp. 1188–1195

[38] Schnürer J., Clarholm M., Rosswall T. Microbial biomass and activity in an agricultural soil with different organic matter contents. Soil Biol. Biochem. 1985, 17 (5) pp. 611–618. DOI:10.1016/0038-0717(85)90036-7

[39] Bratbak G., Dundas I. Bacterial dry matter content and biomass estimations. Appl. Environ. Microbiol. 1984, 48 (4) pp. 755–757

[40] Eekhout J.P.C., De Vente J. How soil erosion model conceptualization affects soil loss projections under climate change. Prog. Phys. Geogr. 2020, 44 (2) pp. 212–232. DOI:10.1177/0309133319871937

[41] Renard K., Freimund J. Using monthly precipitation data to estimate the R-factor in the revised USLE. J. Hydrol. (Amst.). 1994, 157 (1–4) pp. 287–306

[42] Renard K.G., Foster G.R., Weessies G.A., McCool D.K. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). In: U.S. Department of Agriculture, Agriculture Handbook 703, (Yoder D.C., ed.). 1997

[43] A. Demirci and A. Karaburun, "Estimation of soil erosion using RUSLE in a GIS framework: a case study in the Buyukcekmece Lake watershed, northwest Turkey.," Env. Earth Sci 6, vol. 66, pp. 903–913, 2012, doi: https://doi.org/10.1007/s12665-011-1300-9

[44] Panagos P., Borrelli P., Meusburger K., Alewell C., Lugato E., Montanarella L. Estimating the soil erosion cover-management factor at the European scale. Land Use Policy. 2015, 48 pp. 38–50. DOI:10.1016/j.landusepol.2015.05.021

[45] R. P. Stone and D. Hilborn, "Universal Soil Loss Equation (USLE) Factsheet Order No. 12-051," 2011. doi: 1198-712