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Short Communication

Environmental sustainability of an agri-livestock farm: proposal for an integrated indicator

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Abstract

This paper proposes a way to overcome the limitations of the environmental sustainability indicators currently used for agri-livestock production. The reference paradigm is that of safe minimum standards. Five environmental components are considered: soil, water, biodiversity, gaseous emissions and energy. For each, an emergent property is identified and assessed using a single indicator. The five elementary indicators are aggregated following the pathway defined for the assessment of the ecological footprint. The results obtained by applying the proposed methodology to a Tuscan agri-livestock farm show that, although further refinements are possible, the method is sufficiently straightforward to apply.

Keywords: Environmental sustainability, Agri livestock systems, Composite indicator, Natural capital, Farm level assessment.

JEL codes: Q01, Q12, Q15, Q57.

Highlights

- A novel composite indicator for assessing environmental sustainability at farm level is proposed;
- The framework integrates soil, water, biodiversity, greenhouse gas balance and energy use;
- The methodology combines normalised indicators with an ecological footprint based weighting system;
- Application to an organic beef cattle farm shows a high level of environmental sustainability;
- The indicator supports farm management and sustainability oriented decision making.

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1. Introduction

The growing interest in sustainability (EU Commission, 2025) requires the identification of appropriate indicators for measuring it. The difficulties in arriving at shared indicators depend on numerous factors (IIASA, 2025): a lack of agreement on the reference paradigm (Waas *et al.*, 2014), results influenced by the boundaries of the system considered (Hauschild *et al.*, 2024), the need to consider the dynamic dimension (Banos-Gonzalez *et al.*, 2016) and difficulties in aggregating elementary indicators (Gan, 2017).

Two approaches are usually adopted. The first, used mainly at the territorial level, refers to Drivers-Pressures-State-Impacts-Responses (DPSIR) models (Gari *et al.*, 2022). The second approach is based on life cycle assessment (LCA), standardized under ISO 14040 and applied to support policy development and performance-based regulation. Despite its broad adoption, the methodology continues to evolve in response to sustainability challenges and decision-making needs (Guinée J., 2016). Van der Werf *et al.* (2020) identify three problematic aspects of LCA when applied to agricultural systems: soil degradation, biodiversity loss and the effects of pesticide use. These limitations persist (Letcher *et al.*, 2021) relative to the production of ecosystem services and the role of local specificities, even after the most recent methodological improvements (Hayashi, 2023). LCA also tends to favour the assessment of intensive production systems (van der Werf *et al.*, 2020) and entails the risk of using inconsistent indicators (Stefanon *et al.*, 2018).

After the EU introduced the Corporate Social Reporting Directive (CSRD) and the Global Reporting Initiative (GRI) introduced standards such as the GRI 13 for agriculture, approaches for assessing and reporting environmental, social and governance (ESG) performance have become widely used (Macellari *et al.*, 2025). There are numerous applications in the agricultural sector (Wang, 2024), and, with regard to environmental aspects and CSRD application there are many limitations and constraints including limited data availability, the complexity of Scope 3 emissions accounting, and the lack of standardized indicators, particularly for biodiversity and soil health, as already highlighted for LCA (Nolan J. *et al.*, 2026). Moreover, the lack of reference standards may lead to different conclusions for the same case (Berg *et al.*, 2022).

To overcome some of the limitations outlined above, this paper proposes a new indicator for livestock farms, with reference only to environmental aspects. To this end, paraphrasing the classic Brundtland definition (WCED, 1987) and considering guidance from the Food and Agriculture Organization of the United Nations (FAO, 2008), a sustainable livestock farm is defined as one on which production cycles can be repeated indefinitely on the same land areas and using the same techniques. Among the possible paradigms, reference is made to safe minimum standards (Bishop, 1978), interpreted within the logic of minimum safeguards (EU Commission, 2022).

Some of the limitations of the procedures for aggregating elementary indicators are overcome by applying systems thinking (von Bertalanffy, 1971). This suggests focusing on emergent systemic properties, namely those that manifest themselves only at a certain stage in the hierarchical organisation of matter. It is therefore possible to map dynamic interconnections and feedback loops (Rousseau *et al.*, 2020) by using a single indicator for a complex phenomenon, rather than the multiple elementary indices that determine it. In addition, a weighting system inspired by the logic of the ecological footprint (Wackernagel *et al.*, 1999) is used, thereby producing an aggregate of variables that can be referred to an endogenous measure, namely the photosynthetic productivity of land (Galli *et al.*, 2020). Finally, the main components of natural capital considered in relation to agri-livestock system are soil, air, water, biodiversity and energy (Bockstaller *et al.*, 2021). These components are assessed throughout both the agricultural cycle and to the livestock-rearing phase, up to the point at which the animals leave the farm. For purchases of raw materials, the associated environmental resource cost is assessed as though the materials had been produced on the farm.

2. Methodology

For each of the five environmental components, either the stock or the flow is considered as a function of mobility, that is, the distance within which relevant changes occur from the point at which the anthropogenic intervention is applied. Furthermore, for each of the same components it is possible to identify the condition that ensures sustainability. Table 1 reports the assumptions adopted. The following subsections detail observations that may be made in relation to the different components.

Table 1. Mobility of environmental components and related parameter considered.

Environmental component	Scale of impact	Parameter considered	Sustainability ensured if
Soil	Local	Stock	Productivity does not decrease
Water	Regional	Impact of the flow on the stock	Hydrological cycle is not modified
Biodiversity	Local/regional	Stock	Biodiversity stock is not reduced
Air	Global	Flow	Net greenhouse-gas emissions equal to zero
Energy	Global	Flow	Net use of non-renewable energy equal to zero

2.1. Soil

For the vast majority of agricultural activities, soil, a non-renewable natural resource (Nortcliff, 2002), constitutes the necessary physical basis, and its sustainable management appears essential (Montanarella, Panagos, 2021). For sustainability purposes it is important to distinguish between the global and/or territorial level and the farm level. At the former level, it is necessary to consider the availability of land and its allocation among different crops. At the farm level, from a sustainability perspective, it is essential to maintain productive capacity at least at a constant level. This depends on the surface area – which, for the present purposes, may be regarded as invariant – and on the agronomic quality of the soil. The latter represents an emergent property (Lehmann *et al.*, 2020), and it is possible to distinguish between inherent quality and dynamic quality (Doran, Zeiss, 2000). The former is defined by pedogenic factors, whereas the latter may, for the present purposes, also be regarded as influenced by the anthropogenic components of the ecosystem (Bunemann *et al.*, 2018).

The dynamic quality of soil depends on several factors (Karlen *et al.*, 1997), and attempts have been made to estimate it through the biological activity of the microorganisms present (Longa *et al.*, 2017; Menta *et al.*, 2022). The QBS-ar biological quality index is suitable for this purpose (Menta *et al.*, 2022). Six quality classes are usually considered for the QBS-ar index, so it is possible to obtain a normalised index (T1) ranging from 0 for the lowest quality class to 100 for the optimal quality level, with intermediate values obtained by linear interpolation. Sustainability is achieved if the value of T1 does not decrease over time.

2.2. Water

Water is a fundamental resource for all agroecosystems (Garrido, 2023). Its sustainability can be assessed using the hydrological balance (Pereira, 2020). This can be expressed as follows (ISPRA, 2021):

$$[1] P - E = I$$

with $I = R + G + \Delta V$

where P denotes precipitation; E evapotranspiration; I the internal flow; R surface runoff; G aquifer recharge; and ΔV the storage of water volumes in the soil and snow cover.

Equation [1] expresses, in millimetres, the distribution of precipitation in the reference area (Braca *et al.*, 2024). In the absence of irrigation and pollution, crop water can be estimated from evapotranspiration.

In the presence of crops, the local hydrological balance may be perturbed for two reasons: the use of irrigation water (AcIr) and/or service water (AcS), and pollution caused by agronomic practices. Irrigation water is comparable to rainfall: part of it evapotranspires, while the remainder (IIr) increases the internal flow. The volume of grey water (AcG) is equal to the quantity required to dilute pollutants until water quality is again above defined standards. Irrigation water and grey water interfere with the hydrological cycles of other areas. If this interference is high, then non-sustainability is exported.

The volume of water to be considered for assessing sustainability is equal to the water used for crops that interferes with external areas (Ef):

$$[2] (AcIr - IIr) + AcS + AcG = Ef$$

The Standardized Precipitation Index (SPI) (ISPRA, 2021) may be used to assess whether there is tolerable interference with the natural water cycle. The SPI quantifies a rainfall deficit or surplus relative to mean values at different time scales. Using a normalised estimator based on a gamma distribution (ISPRA, 2021), the SPI varies from +2 (extreme wetness) to -2 (extreme drought). The risk of drought, and therefore severe interference is excluded the SPI is greater than -1 but less than +1 (i.e. $-1 < SPI < +1$).

Finally, it is possible to transform the original measures into a normalised index (T2), which assumes a value of 100 when the SPI is within the normal range (-1 to +1) and 0 when it assumes a value of ± 2 . The intermediate values assigned to the intermediate classes can be readily derived by linear interpolation.

2.3. Biodiversity

Biodiversity is a fundamental element for the health of our planet and for human well-being (MEA, 2005). Second-level biodiversity is generally considered for sustainability purposes (Tamburini, 2020).

At the farm level, biodiversity can be assessed by considering the interactions between natural characteristics and management activities (Caporali *et al.*, 2009). Among the methods available, the most comprehensive, but also the most expensive, are based on direct surveys. Defining measurable and verifiable criteria in line with the international objectives of the Global Biodiversity Framework (2022) and European strategies (EU Commission, 2020) is not always straightforward. Generally, the result is an Integrated Ecosystem Performance index (T3), with values greater than 0 indicating sustainability. The resulting value can also be readily converted to an index ranging from 0 to 100.

2.4. Gaseous exchanges

For gaseous exchanges, those associated with the net production of greenhouse gases are considered. Numerous studies have assessed the contribution of livestock farming to the greenhouse effect, expressed as kilograms carbon dioxide equivalent (kg CO₂e). The actual contribution depends on the type of farming system, manure management, feed characteristics, environmental conditions, and breed. The values used must therefore be assessed on a case-by-case basis (FAO, 2023). In the case study examined, the carbon footprint of the livestock system can be estimated at 13.4 kg CO₂e/kg live weight

(Frascarelli *et al.*, 2025). Where appropriate, emissions arising from chemical inputs and the technologies used should also be included.

These emissions are offset by the CO₂ fixed by plants through photosynthesis. At a general level, although with substantial local variability, an absorption rate of 1 t CO₂ equivalent/year/ha may be assumed for pasture, including both grass production and soil uptake (IPCC, 2019). For permanent meadows, 170 kg of CO₂ fixed per quintal of hay may be assumed, of which approximately 20 kg is stored in the soil (IPCC, 2019).

The gaseous emissions balance can be expressed as:

$$[2] \text{ Bmt} = \text{Emt} - \text{Fmt}$$

where Bmt is net emissions, Emt is total emissions, and Fmt is total fixation. To achieve sustainability, Bmt should be less than or equal to 0. An indicator (T4) can also be defined, with a value of 100 when Bmt = 0 (sustainability ensured) and a value of 0 when Bmt = Emt (non-sustainability).

2.5. Energy

The input of external energy (Ee), excluding human labour, can be estimated from the energy contained in purchased technical inputs. Ee can then be compared with the amount of energy obtainable by using the biomass produced to generate energy (Er). According to Fiala (2012), approximately 60 kWh/q can be obtained from hay and approximately 20 kWh/q from grass using biochemical conversion (biogas). Clearly, when hay and grass are used as livestock feed, the corresponding energy cannot offset Ee. T5 will equal 100 if Er is equal to or greater than Ee and will equal 0 if Er is 0, with intermediate values as a function of the Er/Ee ratio. Indicator b5 is a function of the fraction of the total surface area theoretically required to obtain, from the existing crops, an amount of energy equal to Ee.

2.6. An integrated indicator

Within the logic of safe minimum standards, compensation among the five elements considered may occur up to the point at which biophysical thresholds are reached, beyond which the system collapses irreversibly. Drawing on the logic of the ecological footprint, whereby the measures considered are ultimately relate to the photosynthetic productivity of land, it is not necessary to establish such thresholds *a priori* for each individual element. Land productivity itself represents an endogenous measure based on a common unit that incorporates the limits that cannot be exceeded, beyond which the system would collapse, for each of the five components described above. It is therefore possible to construct a synthetic indicator by appropriately weighting the individual indicators:

$$[3] \text{ ISOB} = \text{T1} \cdot \text{b1} + \text{T2} \cdot \text{b2} + \text{T3} \cdot \text{b3} + \text{T4} \cdot \text{b4} + \text{T5} \cdot \text{b5}.$$

The ISOB may be estimated relative to its maximum possible value (ISOBmax) under the specific farm conditions considered. The effective ISOB (ISOB_{eff}) may also be estimated using the actual information obtained from the analyses conducted. The ratio ISOB_{eff}/ISOBmax equals ISOBs. The latter, with a maximum value of 1 and a minimum value approaching 0, represents an overall indicator of the degree of farm sustainability. As noted above, the relative weights (bi) for each component can be derived using an approach analogous to that used to calculate the ecological footprint. More specifically, by referring to the equivalence factor, it is possible to estimate the amount of land devoted to forage

production that would be required to compensate for any excess use relating to the other aspects considered.

- b1 (soil) therefore assumes a value of 1.
- b2 (water) can be estimated as the ratio, per unit area, of water used (Ef) to rainwater (P).
- b3 (biodiversity) can be set at 0.12, by analogy with the share of land considered in the estimation of the ecological footprint (Wackernagel *et al.*, 1999) to be allocated to biodiversity.
- b4 (air) can be calculated as a function of the fraction of the total area theoretically required to absorb total greenhouse gas emissions.
- b5 (energy) is equal to the number of hectares required to produce Ee, relative to the total farm area, considering the theoretical net energy obtainable as dry matter from 1 ha of cultivation.

3. Application to a case study

A cattle farm located in the Valdichiana area of southern Tuscany, with the remaining land area devoted to the cultivation of medicinal plants, was selected as a pilot case study. The animals are reared under semi-free-range conditions and have access to rotationally managed pasture throughout the year. The main data relating to the livestock sector of the farm in 2023 are summarised below:

- UAA, 226.5 ha; hay produced, 4,890 q; hay purchased, 85.17 q;
- Average stocking rate, 101.3 LSU; number of animals, 138.5; number of animals purchased and slaughtered, 77; average live weight, 57,633 kg;
- Water, 162,000 m³ for irrigation and 1,999.45 m³ for watering;
- Purchases, 6,300 L of diesel, 300 kg of salt and 3,400 kWh of electricity.

3.1. Estimates of the indicators

Based on the information collected, the indicators can be estimated as follows.

Soil

For the QBS-ar indicator, the average values obtained in the 2023 surveys, compared with those recorded in 2020/2021, show an increase of 12%. However, the purchased hay must also be considered. Producing it would require 2.06 ha, equivalent to 1.8% of the area devoted to forage crops. The T1 surface-area indicator will therefore be equal to 98.2. Furthermore, on the basis of the observations above, b1 will equal 1.

Water

In this case, there is no grey water, as the animals are on pasture throughout the year. Conversely, the impact of irrigation water must be assessed. To calculate the SPI, monthly precipitation data for the period 1951-2023 at Anghiari (AR) were considered (ISPRA, 2025). The data were processed using a gamma function. In the reference year, the irrigation water used was 60.34 m³/ha/month, corresponding to 6 mm/ha/month. This withdrawal, compared with the estimated function, falls within the SPI interval (-1, +1); therefore, T2 will be equal to 100 and b2 is equal to 0.107.

Biodiversity

In 2024, the farm began a biodiversity survey on the areas considered in this study. Monitoring was based on UNI 17298 and mean species abundance (MSA). The latter was calculated in relation to land use (Alkemade *et al.*, 2009). Monitoring and indicators calculations were conducted by 3Bee and Xnatura, also using satellite analysis. Comparative analysis of the site and the reference habitat showed an MSA index of 51 out of 100. Therefore, T3(a) will be equal to 51, while b3 is equal to 0.12.

Gaseous emissions

Total emissions amount to 789,828.4 kg CO₂e¹, while the total quantity of greenhouse gases fixed is 1,935,729.2 kg². The T4 index is therefore equal to 100, while b4 is equal to 0.045.

Energy

The total amount of energy used is 238,530 MJ. Given that 1 ha of meadow can produce 78,500 MJ, this corresponds to an equivalent area of 3.03 ha. Therefore, to compensate for Ee (Fiala, 2012), 1.47% of the total farm area would need to be allocated to energy production. The T5 index is therefore equal to 74,07, and b5 is equal to 0.015.

Calculation of the ISOB

Based on the estimates for each indicator, ISOBmax will be:

$$\text{ISOBmax} = 100*1 + 100*0.107 + 100*0.12 + 100*0.045 + 100*0.015 = 128.7$$

whereas ISOBeff will be:

$$\text{ISOBeff} = 98.2*1 + 100*0.107 + 51*0.12 + 0*100.045 + 74,07*0.015 = 120.6$$

ISOB will therefore be equal to: $T_s = \text{ISOBeff}/\text{ISOBmax} = 0.937$.

The resulting score, when compared with the evaluation criteria suggested by the United Nations (Sachs *et al.*, 2023), indicates a level of sustainability close to the optimal target and entirely acceptable.

¹The total derives from emissions per kg of animal live weight (57,633 kg*13.4), emissions from diesel used (6,300 l*3.17), and those arising from electricity consumption (3,400*0.256).

²The total derives from the absorption by forage crops (soil + forage), equal to [(4,890 + 85.17)*172], and by pasture (108*10,000).

4. Some final considerations

This work has identified a new indicator for assessing the sustainability of an agri-livestock farm. The results indicate that the proposed methodology is sufficiently straightforward to apply. The choice to focus on an emergent property for each considered environmental component allows a single basic variable to be selected for each component without the loss of information. In this regard, further investigation could address how this representative variable should be measured. The possibility of relating each component considered, either directly or indirectly, to a single variable (photosynthetic productivity) reduces the relevance of issues associated with the aggregation of multiple indicators. However, further analysis of the weights assigned to each component could be useful.

One limitation of the proposed methodology may be the difficulty of collecting adequate information that accounts for the specific conditions of the farms under consideration. In addition, further applications are needed to assess the robustness of the proposed indicators and their applicability to livestock systems that differ substantially from the one examined here. Finally, it may be useful to develop a software tool that enables farmers to calculate their own ISOB and identify areas where management practices could be improved.

Author Contributions

G.G.: Conceptualization, Methodology, Data curation Writing-original draft, Formal Analysis. J.G.O.: Project Administration, Supervision. M.T.: Writing – review & editing, Methodology. D.V. Software, Resources, Investigation, Formal Analysis.

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