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Assessing the Practical Feasibility of Characterizing the Sustainability of Arable Farms by Measuring and Judging Ecosystem Services

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Abstract

A recent report on the future of agriculture by the European Commission emphasizes the need for sustainable development on a farm level to be characterized by measuring ecosystem services with indicators and corresponding thresholds. This case study raises the question whether or not operational methods are currently available to allow such measurements under practical field conditions. To broaden the scope of this case study to the international policy arena, the measurement of ecosystem services was linked to selected UN Sustainable Development Goals (SDGs). The case study showed that operational methods are currently available to measure and judge ecosystem services related to the following: the production of healthy food, water quality, greenhouse gas emissions, biodiversity, and soil health. This conclusion was, however, only possible when applying innovative sensing and laboratory techniques to measure pesticide and heavy metal contents and soil microbiology. Soil health is not only important as an ecosystem service, as such, but also plays a major role in realizing the other ecosystem services. Once all ecosystem services are satisfied on a particular farm, a farmer is free to follow his own unique management practices free from top-down governmental rules and regulations that focus now on required management measures. Each farmer can pursue the goals in a way that best aligns with his own vision, context, and creativity.

Keywords: environmental thresholds; land use; living lab; Sustainable Development Goals (SDGs); outcome-based policy; soil health

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1. Introduction

Two recent high-level reports published by the European Union [1,2] define future scenarios for European agriculture. The strategic dialog [1] was written by leading members of: 11 various agricultural stakeholder organizations, 8 NGOs, 9 industries and two scientists. The dialog thus expresses a strong stakeholder and industry perspective covering the entire production chain. When addressing knowledge in the dialog, the emphasis is on better access and sharing, not necessarily on generating new knowledge, thus presenting an intriguing signal for the scientific community. The research community is challenged in a positive manner when the dialog emphasizes "*the need for sustainable farm management and* *harmonization of methodologies for on-farm sustainability assessment*" with "*common metrics and indicators*" aiming at the following objective: "*to determine where each farm stands*", and to "*provide quantifiable ecosystem services using robust indicators*".

The European Commission presented a follow-up vision for the future of agriculture and food [2] also embracing "*on-farm sustainability assessment*", in the context of "*an agro-food system that is economically, socially and environmentally sustainable*". This involves "*contributions to climate mitigation, providing clean water and air, soil health and biodiversity preservation*".

Though focused on 27 EU countries, these two documents can have worldwide implications. Considering the focus on sustainable development in both documents, it would be pragmatic to frame future activities in terms of the UN Sustainable Development Goals (SDGs) approved by 193 governments in 2015, thus providing a legal foundation for efforts to be made (https://sdgs.un.org/goals (accessed on 5 January 2026)). It also provides a pro-active signal to society at large that agriculture contributes to sustainable development [3–7]. A focus on ecosystem services provides basic emphasis on environmental aspects in contrast tocurrent environmental rules and regulations that emphase required forms of management without a link to sustainability [8]. Emphasis on SDGs provides a clear "*Point-at-the-horizon*" with general societal significance by requiring the determination of ecosystem services, defined as "*contributions by ecosystems to mankind*" [9]. Ecosystem services are characterized by indicators and thresholds and correspond with Key Performance Indicators (KPIs) that are widely used in the business world [10].

Emphasis on studies at farm level by the European Union is not new. They have promoted research in Living Labs [11], defined as "*spaces for co-innovation, through participatory, transdisciplinary systemic research*". Living Labs reflect the need for researchers to work closely with stakeholders that contribute their tacit knowledge, thereby jointly developing practical solutions to overcome barriers to sustainable development. This bottom-up procedure is in contrast with current top-down rules and regulations. When successful, Living Labs become Lighthouses, defined as "*single sites, like a farm or a park, where to showcase good practices. These are places for demonstration and peer-to-peer learning*." Every farm is a Living Lab and every farm is different, even in the same region and on similar soils, as each individual farmer cherishes his or her own particular practices of adaptive management. This represents his or her basic strength and identity. When this is not recognized and mobilized, sustainable development in agriculture may remain a distant dream.

Numerous scientific methods have been developed to separately measure the status and quality of soil, water, air, and nature, as addressed by corresponding SDGs. But when assessing sustainability at a farm level, as suggested by [1,2], such a set of different methods will have to be combined into a comprehensive package that is both operational and cost-effective. To be feasible in practice, the system has to be relatively simple and straightforward and not too expensive. Some existing studies use modeling and focus on regions or entire countries [12–14]. These approaches provide valuable insights, but the next step is to downscale them to the farm level—treating farms as Living Labs—to enable practical application and direct contributions towards future EU agricultural objectives.

The objective of this article is therefore to achieve the following: (i) investigate whether currently available methodologies, characterizing ecosystem services, are suitable and adequate to be routinely applied on a farm level, and (ii) define the role of soils when contributing to ecosystem services. A previous study [6] tested methodology on one field, while this study covers additional operational procedures applied to a complete farm, also considering the costs involved.

2. Materials and Methods

2.1. Ecosystem Services in Line with Relevant SDGs

A limited number of the seventeen SDGs are of primary interest for arable farming systems in The Netherlands. Seven such goals are shown in Table 1 and Figure 1.

Table 1. A selection of SDGs that are of prime significance for arable farming systems in The Netherlands and beyond in Western Europe. The corresponding ecosystem services can also serve as Key Performance Indicators (KPIs) as used in the business world.

SDG		Corresponding Ecosystem Service
1	No poverty	Farmer income
2	Zero hunger	Production levels
3	Good health and well-being	Healthy products
6	Clean water and sanitation	Clean ground and surface water
13	Climate action	Emission greenhouse gasses
15	Life on land	Biodiversity/nature and soil health

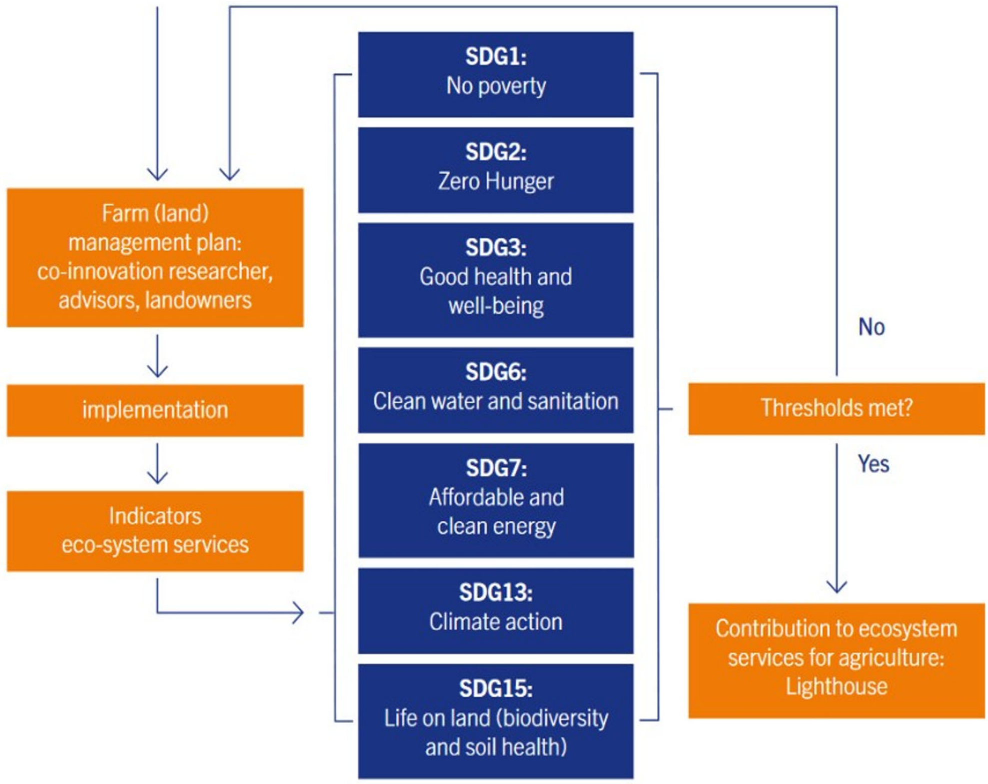

Figure 1. Flow chart demonstrating the procedure to test whether ecosystem services, contributing to achieving the most relevant SDGs for Dutch agriculture, meet thresholds that apply to the Living Lab being studied [5].

The position of SDG1, which relates to farmer income, is essential when assessing the sustainability of a given farming system. Obviously, when farmers' income is inadequate to make a living, their farming operation is not sustainable. As discussed, sustainable development has an economic, social, and environmental dimension. This paper focuses on the environmental dimension, in line with the focus of the EU reports discussed above [1,2]. This information is crucial when assessing economic and social aspects to be expressed in environmental policies, including subsidies and rules and regulations.

How about the remaining ten SDGs? Sustainable development has economic, social and environmental dimensions and the remaining SDGs have a more social and economic character, even though environmental aspects are still relevant. Quality education (SDG4) is important and can be supported by providing clear examples of sustainable farming systems, as proposed in this study. Gender equality (SDG5) and reduced inequalities (SDG10) are less relevant for Dutch conditions, although promoting equality remains a critical pillar of sustainability and should be actively safeguarded to ensure fairness, inclusivity, and long-term resilience. Peace, justice, and strong institutions (SDG16) and partnerships for the goals (SDG17) are important but beyond control of individual farmers. Industrial innovation (SDG9), sustainable cities (SDG11), and life below water (SDG14) have a different focus. Affordable and clean energy (SDG7) can be considered by the proportionality principle: agriculture uses only 7% of national energy in The Netherlands and many farms now have sun collectors or windmills generating electricity. Conserving energy at a national level will require prime attention for industry, building, and traffic. Decent work and economic growth (SDG8) is indirectly reflected by SDGs 1, 2, and 3: a good income, based on producing sufficient healthy foods. Responsible consumption and production (SDG12) is represented by the focus on SDGs 2 and 3, while individual farmers can contribute to responsible consumption by producing healthy food (SDGs 2 and 3).

Again, ecosystem services are defined as "*services the ecosystem provides to man*" [9]. Provisioning ecosystem services relate to healthy food (SDGs 1, 2, and 3) and clean water (SDG6); regulating services relates to climate action (SDG13) and supporting services relates to biodiversity (SDG15). This way, ecosystem services are systematically linked with the SDGs that were not yet defined when the ecosystem services were introduced by the Millennium Ecosystem Assessment in 2005. Soil health can be considered to be an ecosystem service by itself (part of SDG15). Of course, economic and social conditions have a major if not dominant impact on the seven SDGs mentioned in Table 1. But a systematic analysis of ecosystem services, as proposed by the recent reports of the European Union, and as explored in this paper, can provide a quantitative basis for economic and social analyses and for future actions.

2.2. The Farm Being Studied

The Rodenburg farm covers 30 ha and consists of four fields, which is relatively small. The average size of arable farms in The Netherlands is 60 ha. But sizes vary widely: 25% are smaller than 19 ha and 25% are larger than 82 ha (https://www.cbs.nl/nl-nl/achtergrond/2025/14/feiten-en-cijfers-over-de-landbouw (accessed on 5 January 2026)). A medium-textured clay soil (23% clay) (MN35A in the Dutch soil classification) is dominant and a heavy clay soil (32% clay) (Mn45A) occurs as a small strip in the southern part of the farm occupying 15% of the entire land area. The Mn35A is classified as a fine, mixed, mesic Typic Fluvaquent in the US Soil Taxonomy system [15] and as a Eutric Fluvisol in the FAO World Soil Reference base [16]. The Mn45A has the same classification but is very fine, mixed, and mesic. Potatoes, sugar beets, and winter wheat are grown in rotation and cover crops are part of the management scheme. The farm is relatively small and, even though the farmer owns the land, this still means that major investments are difficult to realize. Income from farming operations is not adequate. The farmer has therefore remodeled one of the sheds as a conference center, which is successful. Side activities by farmers are also increasing elsewhere and can consist of a shop selling local produce or providing locations for meetings, conferences, weddings, etc. Emphasis in this study is on environmental aspects of sustainability, as discussed above.

2.3. Methods for Measuring Indicators and Selecting Thresholds for Ecosystem Services

The four fields of the Living Lab were sampled following well-tested procedures applied when sampling for fertility recommendations [17]. These procedures reflect spatial variability and produce representative data by mixing and combining a large number of separate samples obtained from any field by a systematic sampling scheme that has been tested in the literature. Analyzing all separate samples would be far too expensive.

SDG1 was discussed above.

Production levels (SDG2) can be compared with national and regional yield levels reported in the literature. A theoretical approach can also be followed by running simulation models for crop growth where a threshold of 80% of the water-limited yield (Yw) can be applied [18]. Yw assumes optimal availability of plant nutrients and lack of pests and diseases.

Healthy products (SDG3) result from plants grown on healthy soils free from pollutants, such as heavy metals and biocides. The latter will be determined when assessing soil health, to be discussed later.

Water quality (SDG6) was measured by following the requirements of the EU Water Guideline [19]. The chemical indicator for groundwater is the nitrate concentration with a threshold of 50 mg/L NO^{3-}/L. For surface waters, N-total and P-total are considered, with thresholds of 4 mg/L and 0.3 mg/L, respectively. Biological indicators for water quality use the EQR score (Ecological Quality Ratio): water flora, macrofauna, and fish, all with thresholds, 19 of 0.50. But this Living Lab was not connected with surface water, as it is separated by a dike from an adjacent lake, and surface water quality will therefore not be further discussed here.

Emissions of greenhouse gasses CH_4 and N_2O (SDG13) were estimated for this particular region [12,20]. CO_2 emissions for this Living Lab were estimated by the soil health indicator in terms C-sequestration [21] and were compared with regional values as presented by [12,20] to allow an estimate of a threshold value.

Biodiversity, one element of SDG15, must be considered in a regional context, and no clear indicators—let alone thresholds—are currently defined that apply to individual farms acting as Living Labs. In the context of the European Natura 2000 program, 162 protected nature areas have been designated in The Netherlands to protect and improve biodiversity (https://www.natura2000.nl/) (accessed on 5 January 2026). For the Living Lab under study, the nearest Natura 2000 site is the Voornse Duin, located 9 km away. There are, as yet, no legal requirements for biodiversity at a farm level but some management measures may contribute to the improvement of soil health indicators. An example is a higher organic matter content of soils as a result of growing cover crops. The primary responsibility of any agricultural Living Lab is to prevent the release of pollutants into air and water that could affect nearby nature areas. The extent of such emissions can therefore serve as an indicator of the farm's contribution to the preservation of regional biodiversity. Soil health forms the second element of SDG15 and will be discussed below.

2.4. Methods Measuring Indicators and Thresholds for Soil Health

The second element of SDG15 is soil health. So far, there is still debate in the international literature on a standard set of indicators for soil health [22,23]. The EEA has defined soil health indicators in terms of a relation with a number of soil threats: compaction, loss of nutrients, pollution, and loss of soil carbon or of biodiversity. Actual soil conditions can be characterized by soil physical, chemical, and biological indicators with thresholds showing whether or not threats have materialized. There is, however, also a tendency to restrict the number of indicators for practical reasons. For example, the US Soil Health Institute originally had 20 indicators, but that number has now been reduced to 3 (https://www.soilhealthinstitute.org (accessed on 15 December 2025)). Combining the need to have a relatively simple system while covering physical, chemical, and biological aspects of soil health, we used a system defining indicators and thresholds for the following: (i) physical aspects of soil health (e.g., electrical conductivity, soil structure, and soil moisture regime); (ii) chemical aspects of soil health (soil fertility, pollutants); (iii) biological aspects of soil health (soil biodiversity); and, in a central position, (iv) carbon (carbon content and various carbon compounds) [6,22] (Figure 2). This procedure is in line with the EEA proposal [23].

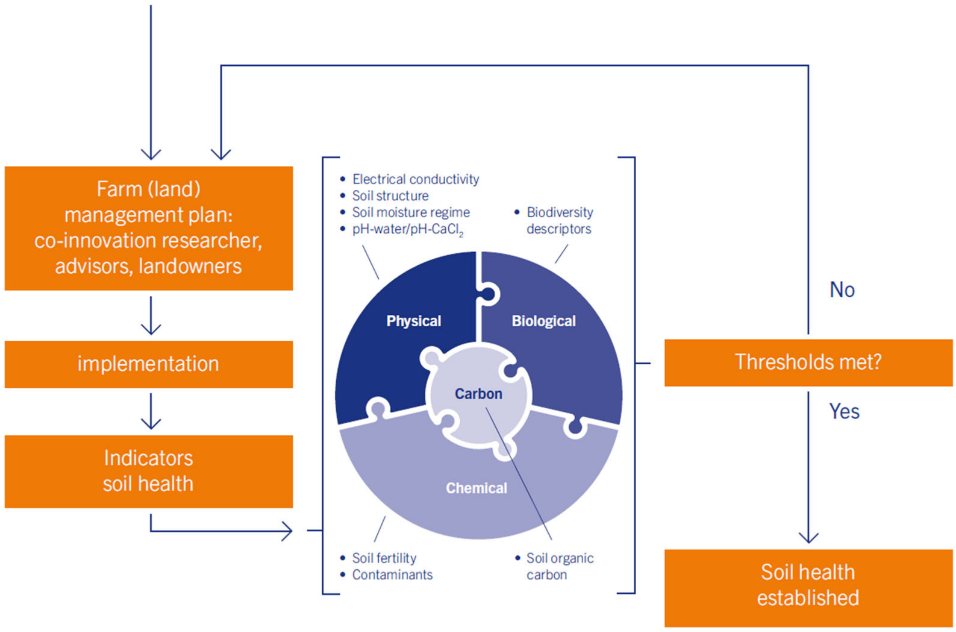

Figure 2. Flow chart demonstrating the procedure to test whether soils are healthy with the objective to maximize soil contributions to ecosystem services, shown in Figure 1. Soil health is also a separate element of SDG15 [5].

Electrical conductivity is a measure allowing the distinction of saline soils.

Soil structure can be characterized by descriptions, as used in soil survey, and by the measurement of bulk densities or penetration resistances, using widely used standard procedures [24].

The **soil moisture regime** is still widely represented by the "available water" concept, which is a static parameter based on the difference in water content between field capacity and wilting point, following a theory of the 1930s. Although this may provide a very general initial indication, we opted in this study for a modern, dynamic modeling approach to assess the soil moisture regime, as it aligns more closely with a current understanding of soil–plant–water interactions. Specifically, innovative quantitative land evaluation was applied using a hydropedological classification of 368 Dutch soil types [25], resulting in 79 units that show comparable hydraulic conductivity and moisture retention properties [26]. These units facilitate dynamic modeling of soil moisture regimes using the SWAP-WOFOST model [27].

Chemical aspects of soil health cover **soil nutrients**, including pH and macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) [17]. These nutrients are already monitored by 85% of Dutch farmers through professional fertilization advice based on soil testing. Separate measurement of soil nutrients for a soil health analysis would be redundant if this soil testing already occurs and is being implemented by the farmer, as was the case in our Living Lab. Clear relations are found between soil nutrients and the nutrient content of crops, affecting their culinary quality [28,29].

The presence of **soil contaminants** in the form of **heavy metals**—an important aspect of the soil health assessment—was investigated using a 0.01 M $CaCl_2$ extraction procedure.

After drying, milling, and sieving (2 mm), (heavy) metals are extracted at a 1:10 ratio for two hours at 20 °C, and metals in the filtered extract are quantified by ICP-MS. Analytical quality is ensured through reference samples, duplicates, and ring tests [30]. These bioavailable metal concentrations form an essential part of assessing soil health in relation to SDG3 (healthy products) with defined threshold values.

Additionally, pesticide residues were measured using the Quick Polar Pesticides (QuPPes) method [31] (https://eurl-pesticides.eu (accessed on 15 December 2025)). For pesticide residue analyses, two methods are routinely used. For gas chromatography–mass spectrometry (GC-MS), soil samples are spiked with isotope-labeled standards, extracted with acetone and dichloromethane, dried, concentrated (~1 mL), and analyzed using a nonpolar capillary column with mass-selective detection. For liquid chromatography–tandem mass spectrometry (LC-MS/MS), samples are spiked with isotope-labeled pesticides, extracted, concentrated (~1 mL), and analyzed via reversed-phase high-performance liquid chromatography (RP-HPLC) coupled to tandem MS with electrospray ionization in multiple reaction monitoring (MRM) mode.

Biological indicators of soil health were assessed by phospholipid fatty acid (PLFA) analysis, which provides detailed information on microbial community composition. Threshold values for interpretation were derived from the established literature [32–36]. The (PLFA) analysis quantified living microbial biomass and broad microbial community composition in soil. Soil lipids were extracted using a modified Bligh-and-Dyer protocol (chloroform–methanol buffer), after which total lipids were fractionated on a silica column into neutral lipids, glycolipids, and phospholipids. The phospholipid fraction was derivatized to fatty-acid methyl esters (FAMEs) using base-catalyzed methanolysis. GC-MS was applied for all analyses. PLFAs were identified using reference FAME libraries, and microbial groups were inferred from established biomarker lipids. To enable large-scale implementation in routine soil testing, we additionally developed a near-infrared spectroscopy (NIRS) calibration for key PLFA traits [16].

Carbon occupies a central position in the soil health model shown in Figure 2. As noted in the above discussion of SDG13, soil respiration—calculated via mineralization rates—is another important measure of soil biological activity. Soil organic and inorganic carbon were both assessed for CO_2 sequestration because they represent distinct, complementary carbon pools [20].

3. Results

3.1. Ecosystem Services

The farmer (SDG1) considered his income from agriculture to be acceptable considering the size of his farm but revenues of his side activities were important to allow this positive conclusion. This private opinion is adequate for SDG1 in the context of this paper, which focuses on environmental aspects of sustainability.

Production levels (SDG2) were as follows: sugar beet: 72.7–98.4 tons/ha; potatoes: 51–55 tons/ha, and wheat: 9.2–10.2 tons/ha. They compare favorably with average yields on a national level, which are 75–88 tons/ha for sugar beet, 40–42 tons/ha for potatoes, and 7.0–9.0 tons/ha for wheat (www.CBS.nl (accessed on 5 January 2026)). But data on a national level also reflect relatively unfavorable growing conditions in other parts of the country. Yields in this area with relatively fertile soils are higher. Yields of 100 tons/ha of sugar beet and of 50 tons/ha of potatoes, for example, are being reached here. Actual yields were higher than the theoretical level of 80% Yw. Also, considering the large variation among years due to weather conditions (to be shown later in Figure 4), the conclusion can be that the yield thresholds were met.

When considering health and well-being (SDG3), healthy crops can only grow on healthy, unpolluted soils. The bioavailable (heavy) metal analyses covered Al, Ti, V, Ar, Cd, Cr, Pb, and Sn [30]. All results were below detection level, except for one field where Cd levels just reached the threshold (0.01 mg kg^{-1} soil), and this was reported to the farmer who will pay particular attention to this field in future. The biocide analyses covered more than 400 biocides. All values were below the threshold of 0.01 mg/kg soil, except for the herbicide diflufenican and the fungicide fluxapyroxad in one of the fields, where values reached their threshold. Even though the threshold was not exceeded, the farmer was advised to critically watch future applications. Overall, thresholds were met.

The groundwater quality (SDG6) was measured at six locations and had a range of 6–15 mg nitrates/L which is well below the threshold of 50 mg/L. Biocide levels were below detection level. Average values for nitrate levels in this region of 13 mg/L were reported [12]. The nearest surface water is the large "Brielse Meer", separated from the farm by a dike. The water quality of this lake is affected by many sources and possible contributions by this particular farm are bound to be minor.

Emission of greenhouse gasses (SDG13) was estimated through C-sequestration [21] (Table 2). Calculated mineralization rates and the associated greenhouse gas release were relatively low, which is typical for clay soils with a modest organic matter content. The expected mineralization ranged between 1625 and 2330 kg C ha^{-1} yr^{-1}, as estimated using the Soil Carbon Check system [21] (Table 2). Importantly, the soil organic carbon status has remained stable over the past decades, indicating that these soils continue to retain their carbon stocks. The routine soil test also provides recommended application rates of organic materials to maintain current soil carbon levels, which correspond to the mineralization rate. Additionally, it includes an estimate of the inputs required to meet the French 4‰ (4 per 1000) initiative, aimed at increasing soil organic carbon by 0.4% per year globally. This demonstrates that, following this approach, soil carbon sequestration could theoretically offset the annual increase in worldwide greenhouse gas emissions.

Table 2. Representative results of the carbon section of the soil health indicator [22], for the two soil types as applied in the four fields of the Living Lab.

Indicator	**Mn35A**	**Mn45A**
Soil organic carbon (SOC), %	1.5–2.0	2.5
Soil inorganic carbon (SIC), %	1.31–1.34	0.98
Total carbon content (TC), ton C/ha	53.2–61.4	155.5
Soil organic matter (SOM), %	2.9–3.7	4.7
Mineralization, kg C/ha/year	1625–1965	2330
Mineralization, ton CO_2/ha/year	6.0–7.2	8.6
4 per 1000 requirement, ton CO_2/ha/year	0.8–1.0	1.2

Emissions of greenhouse gases CH_4 and N_2O in Flevoland are the lowest of all provinces in The Netherlands (SDG13) [12]. On a national level, total emissions of greenhouse gases are estimated (2019 data) to be 160 Mton CO_2 eq/yr (www.emissieregistratie.nl (accessed on 15 December 2025)). Most of this (84%) is generated by industry, electricity generation, traffic, and construction. At 26 Mton CO_2 eq/yr, agriculture contributes 15% of the total. But, of that quantity, only 8 Mton is attributed to CO_2 (5% of the total), while CH_4 and N_2O contribute 18 Mton (11% of the total). Methane emission is particularly associated with dairy farming and is not relevant for arable farms like the Living Lab being considered, while N_2O emissions are also low in the well-drained soils found here. On a national level, CO_2 emissions in arable farming are therefore very low, at 5% of the total. This is confirmed for arable land on clay soils in the LULUCF analysis on greenhouse gas emissions reporting to the International Panel on Climate Change [20]. Again, in terms of proportionality, greenhouse gas emissions in the Living Lab being considered are not a primary target for environmental concern. The conclusion is a positive judgment on SDG13.

Biodiversity (SDG15) has to be considered in a regional context when described as an ecosystem service. As discussed above, so far, there is no legislation for on-site above-ground biodiversity on a farm level. As shown by our analyses, this farming system does not discharge pollutants to the environment which, as such, is a contribution to regional biodiversity. Also, as mentioned above, the nearest NATURA 2000 area is 9 km away.

3.2. Soil Health

When considering **physical aspects**, measured EC values were far below threshold levels of concern, as there is no marine influence.

Soil structure was described and showed very large next to small clods in the upper 30 cm of the soil and large soil prisms below that depth (Figure 3). Bulk density measurements were omitted during the field study due to the high spatial heterogeneity of the soils studied (Figure 3), which introduced excessive variability using standard small-core sampling methods. Penetration resistances were generally below 1000 kPa in the upper 30 cm of the soils but higher in the subsoils where values of up to 3000 kPa were reached in soil Mn35, while Mn45 showed lower values of 1000 kPa to 1600 kPa. A major reason for assessing soil structure is to define the rooting environment, and observing rooting patterns was therefore emphasized in this study, showing that roots could reach the subsoil in all soils, bypassing dense clods (Figure 3). In the subsoil, these roots follow the vertical faces of soil prisms where free water also moves downwards, following the bypass flow along the walls of the cracks. This allows more water uptake than is obtained by lateral diffusion from the prisms. As discussed elsewhere, water flow in structured soils requires different approaches than flow in homogeneous, isotropic soils, which is the basis for physical flow theory [37,38]. Prisms are dense and penetration resistances are therefore relatively high, but this does not reflect rooting along the faces of the prisms. The observation of rooting patterns was therefore important in this study to show that roots reached the subsoil, allowing water uptake that could result in crop yields as reported. This analysis demonstrates that field research remains essential to obtaining meaningful data.

Figure 3. Surface soil (0–30 cm) of the Mn35A covered by a wheat crop in May 2025, consisting of small and large clods and roots that reach the subsoil following pores between the surface clods into the cracks in the subsoil.

To characterize **soil moisture regimes**, simulations were made for various crops, of which only results for winter wheat are shown (Figure 4). The model calculates actual yields, taking into account actual soil moisture regimes, while assuming optimal fertilization and lack of pests and diseases.

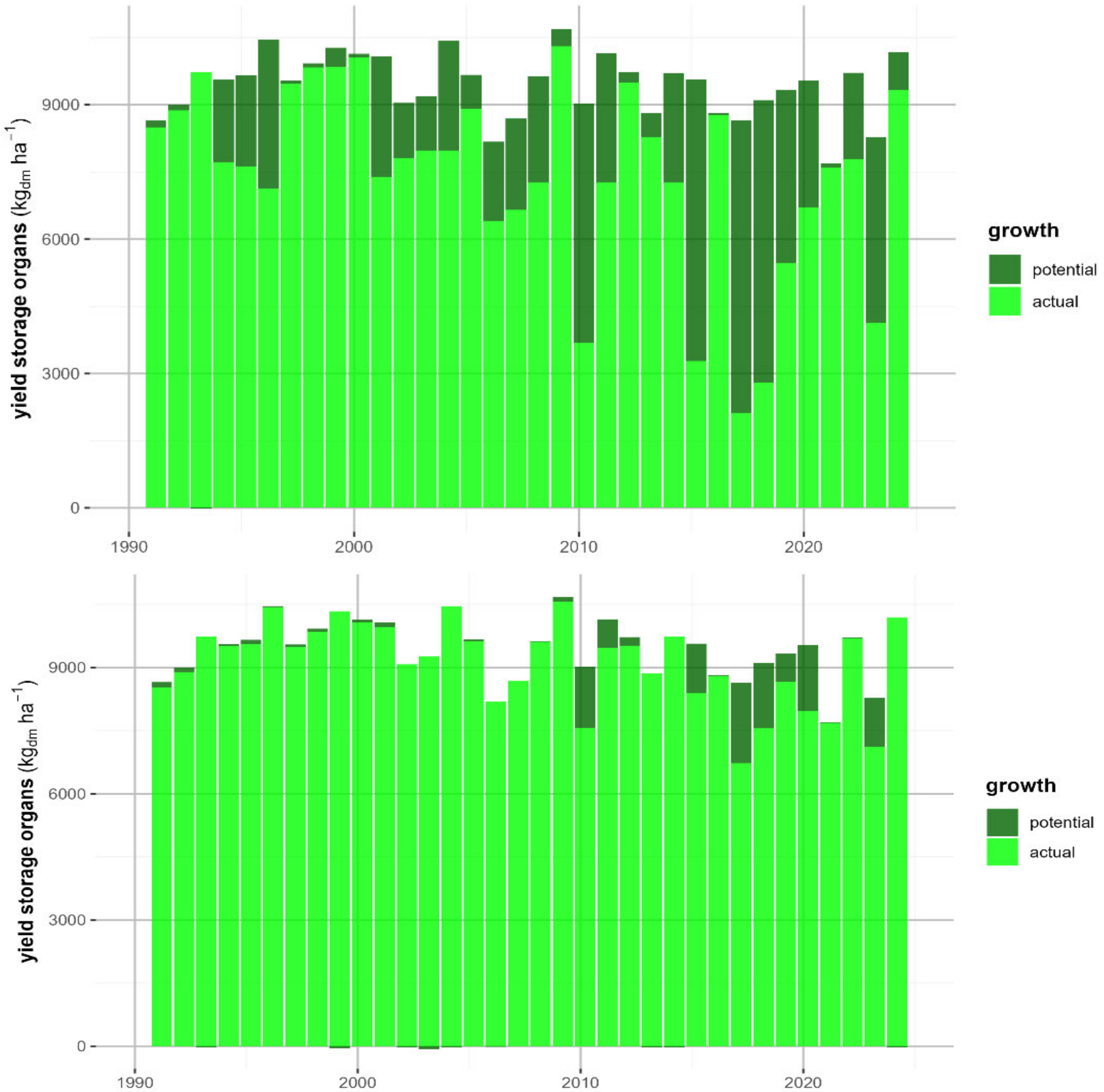

Figure 4. Model calculations of water-limited and potential yields of winter wheat of the Mn35A soil (upper diagram) and the Mn45A soil.

Potential yields also assume optimal availability of water. Calculations were made for a 30-year period showing major variabilities among the years due to weather differences, demonstrating that the soil moisture supply to plants is very much a function of weather conditions. In some years calculated actual yields were identical to potential values, particularly in Mn45A. But in dryer years major differences occur between actual and potential yields due to inadequate moisture supply. How to express these results in terms of an indicator for soil health? The analogy of soil health with human health is helpful here. A "thirsty" person is not necessarily unhealthy, nor is a "thirsty" soil. The simulation data show that even the Mn35A soil can achieve potential yields when weather conditions permit. A crucial element is the depth of rooting as the model assumes rooting to a depth of 80 cm. Quite different results would be obtained with shallow rooting, for example, when a compact plow-pan would be present. Our field observations have shown that roots reach the subsoil even though some of the water and nutrients may be less available in the cloddy topsoil. Still, calculated yields are of the same order of magnitude as the measured ones and 80% of the calculated water-limited yields (Yws) are well below real measured yield values, satisfying the proposed international yield threshold criteria [18]. Yw only reflects water availability and assumes that adequate nutrients are supplied and pests and diseases are absent. This is a reasonable assumption for the Living Lab being discussed but will not apply to many other farms elsewhere.

Because of deep rooting the indicator for the soil moisture supply for the two soils considered here is positive. Finally, the difference between actual and potential calculated yields provides an indication for irrigation needs.

Chemical aspects were assessed through standard soil nutrient analyses used for crop- and soil-based recommendations (Figure 5) [17]. Although plant-available P (soil P-intensity) was relatively low, the soil exhibited a sufficient capacity to supply P from its reserves (soil P-quantity), indicating a low risk of P leaching. Both soil K-intensity and K-quantity were high, implying that no additional mineral K fertilizers were required beyond the organic inputs. The high soil pH likely limited the availability of Cu, Fe, Mn, and Zn, while simultaneously increasing Mo availability to crops. These chemical indicators were monitored throughout the growing season.

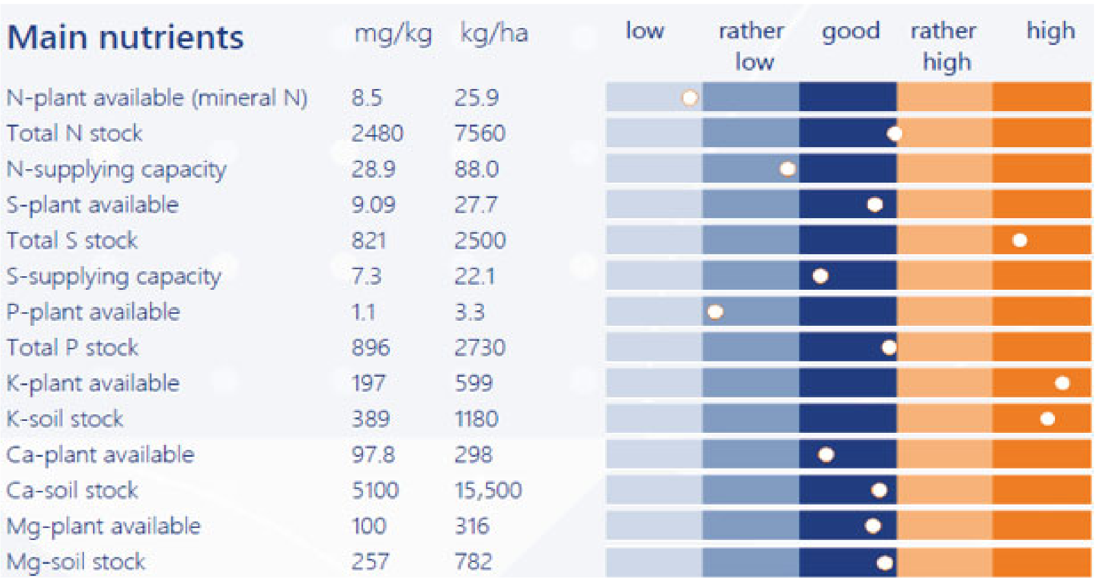

Figure 5. Results of the analyses of essential nutrients as part of standard fertilization recommendations provided to the farmer. Sampling occurred at the beginning of the growing season. Analyses were made for each of the four fields. Data shown here are representative for results obtained.

Results of soil **biological** analyses are reported in Figure 6. The values are average to moderately high, but none are excessively elevated, which is considered positive. This balance between measurements supports the idea that microbiological diversity is important, and that no single group should dominate or be underrepresented.

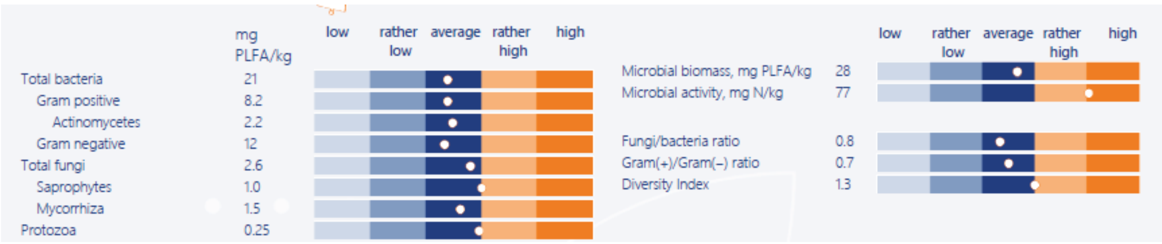

Figure 6. Biological indicators as determined by the QuPPe method (see Section 2). Data were obtained for the four fields and this analysis of a Mn35A soil is representative for the other fields.

4. Discussion

Linking the two recent publications of the European Union on the future of agriculture to the UN-SDGs allowed a definition of ecosystem services in line with a limited number of SDGs that are particularly relevant for Dutch agriculture and for West European conditions. Defining indicators and thresholds for these ecosystem services allowed a judgment as to the degree of sustainability of the farm being studied (the Living Lab). The sustainability mark is obtained when all indicators meet their threshold. This result was obtained for the farm being investigated. When indicators do not meet their respective thresholds, attention can be focused on the ones that need improvement, developing alternative forms of management based on the literature, Lighthouses on similar soils, or newly focused research.

This procedure has a number of advantages: (1) clarity about goals, rules, and regulations is offered to the farmer which (s)he is very eager to receive; (2) transparent links can be made with subsidy payments, including substantial farm support by the European Union [2]; and (3) research can be focused on ecosystem services that do not yet meet their threshold and on obtaining representative thresholds when thresholds are poorly defined. Obtaining operational thresholds for ecosystem indicators is a logical follow-up on many studies relating soils to ecosystem services [23,39,40].

Environmental research has been successful in the past but efforts often had a disciplinary character that has, no doubt, greatly contributed to our understanding of ecosystem functioning. But now we also need an integrated approach, as presented in this study, where all ecosystem services have to be served at the same time. This paper shows that techniques are available now, but only after including modern, innovative ones, and they can be applied to assess whether or not sustainable development is being reached by a given Living Lab. Soil science contributes a soil health assessment to the overall testing of ecosystem services in line with the EU definition of soil health: "*the continued capacity of soils to contribute to ecosystem services*" [11]. Soil science is important, but so are hydrology, climatology, ecology, economy, and sociology.

Soil health is not only considered separately in SDG15 but also contributes to the other ecosystem services such as the production of healthy foods (SDG2 and 3) and climate mitigation by carbon capture (SDG13). Nitrate pollution of groundwater is not only a function of fertilizer applications but is also strongly affected by soil processes as water moves downwards through the soil (SDG6). Biodiversity is also strongly affected by soil health (SDG15). Soils are the most permanent part of the ecosystem and their preservation needs to have a high priority, more so since a decrease in soil health is often difficult to reverse. Emphasizing these functions with clear examples is the best way to promote the profession. Yes, there is "A Golden moment for Soils" [41], but the proof of the pudding is in the eating.

But there is one more crucial aspect. The scheme will only work when farmers embrace it, and this requires any system to be relatively simple and transparent and not too costly.

Our study has addressed this requirement by limiting the number of SDGs to be considered and by defining indicators for ecosystem services with regionally valid thresholds that are relatively easy to measure. Soil testing for fertilization purposes is widely applied in The Netherlands and can be extended to include additional measurements for ecosystem services other than the production of healthy crops.

Costs are €35/ha and include soil fertility, mineral nitrogen, carbon, and biological sampling. Analyses of heavy metals and pesticides would cost an additional €45/ha each. Water quality sampling is €25 per location. For this 30 ha farm, total expenditures amounted to approximately €3150. According to the farmer, the additional diagnostic information enabled substantial adjustments in nutrient management, particularly in the potato crop, where mineral N applications were reduced by approximately 100 kg/ha. The allowance for N applications to green manure was eliminated by recent regulations. As the farmer still wanted to provide N for the green manure, he reallocated the N saved when fertilizing potatoes as a starter dose for the green manure in autumn, together with compost and goat manure.

As is, farmers are highly critical about the actions of government and of the administrative burdens of environmental regulations [42]. Such valid concerns can be addressed by the proposed system: once all indicators for ecosystem services are positive, the farmer will be free to follow his or her own management expertise for a limited period of, for example, five years without regulatory interference.

5. Conclusions

1. The European Union focuses on sustainability when defining future agriculture. Linking future research to ecosystem services in line with the UN Sustainable Development Goals (SDGs) can therefore provide a pro-active and positive signal about agriculture to society at large, the policy arena, and the farming community.
2. Our study shows that the introduction of innovative sensing and laboratory methods has resulted in the practical feasibility of measuring and judging ecosystem services associated with SDGs, which address the production of healthy crops, water quality, the emission of greenhouse gasses, biodiversity preservation, and soil health. Determining relevant threshold values for each of these ecosystem services still requires additional research.
3. Soil is the most permanent component of ecosystems and soil health is an important ecosystem service by itself as part of SDG15. Soils also play a key role when assessing the other ecosystem services. Showing this role with specific examples is the best way to promote soil science in future.
4. Any future measuring system needs to be relatively simple, transparent, and low cost to allow acceptance in practice both from an operational and regulatory point of view. Applying the proportionality principle, attention should only be focused on ecosystem services that are of primary interest for the region where the Living Lab is located. In our study, a choice was made for six crucial environmental SDGs while the nutrient status of soils, an important indicator for soil health, was derived from standard soil sampling for fertility advice, thereby avoiding separate, repetitive measurements.

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