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# Knowledge base on the ecosystem services concept, on technologies and data support systems for soil ecosystem services and on soil health business models.

# Kennisbasis over het concept ecosysteemdiensten, over technologieën en datasystemen ter ondersteuning van bodemecosysteemdiensten en over verdienmodellen voor bodemgezondheid.

**ILVO**
Instituut voor Landbouw-,
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## Executive Summary

This report reviews the state of the art in soil-related ecosystem services (ESS) concepts, monitoring systems, business models and monitoring technologies, and questions whether they can support practical reward schemes for farmers and land managers.

The concept of ESS is widely used across policy and research, but definitions and classifications are still not harmonized. Several ESS frameworks coexist with different terminologies and structures, and soils are often hidden inside broader categories. CICES v5.1 is the most detailed and widely used classification system of ESS in Europe, but it is complex and not fully adapted to soil. When it comes to soil, there is ongoing confusion between soil functions or processes (what soils do) and soil ecosystem services (the benefits people receive from those functions). Recent works have tried to resolve this by defining subsets of CICES classes that are clearly soil- and management-related and suggesting shortlists for more standardized assessments but this is not widely applied yet.

Soil monitoring systems are widespread but mostly not ready to directly monitor soil ESS. Many EU-level and national initiatives mainly track standard soil quality indicators: soil organic carbon, macro- and micronutrients, pH, cation exchange capacity, base saturation, texture, bulk density and contaminants. Biological indicators, and explicit ESS metrics are rarely included. Analysis and sampling methods differ between countries, which limits data sharing and comparison. The new EU Soil Monitoring and Resilience Directive (Soil Monitoring Law (Directive (EU) 2025/2360, 2025)) sets common indicators and criteria for "healthy soils" by 2050 and explicitly links soil condition to multiple ESS, but it does not specify robust, quantitative links from these indicators to concrete ESS metrics at farm scale yet.

In parallel, economic incentives and business models for soil-related ESS have expanded. The inventory underlying this report identified 92 programmes, of which 48 qualify as business models with at least partial private or market-based funding. Most of these use direct payments under a Payment for Ecosystem Services logic, 4 use labels or certification, and 1 uses financial advice as the main incentive. Across all 92 programmes, carbon sequestration is cited 75 times, biodiversity 62 times and water-related services 60 times, while erosion control, flood control, pollination and climate resilience are mentioned far less often. Monitoring in these schemes relies mainly on soil parameters and farming practices, particularly soil organic carbon. Compared with earlier approaches, there is a growing shift towards more quantitative and results-based monitoring, especially in private programmes. Many schemes, especially carbon farming initiatives, only partially disclose their indicators and methods, which limit transparency and comparability.

Technologies to monitor soil-related ESS are inventoried and the advantages and disadvantages of the different techniques are described. The report lists tractor-mounted and handheld soil scanners, in-situ soil sensors, remotely sensed information from drones or satellites and data platforms. Scanners, sensors and remote sensing images measure both direct and indirect soil parameters. In practice, their use is constrained by the need for local calibration, the fact that many methods require bare soil, which is becoming less common due to the increasing use of cover crops and crop residue retention. In addition, optical satellite use is strongly limited by cloud cover in Europe, and drone regulations are strict. Data platforms and exchange systems are expanding. However, datasets remain fragmented across private platforms. Although APIs are available, true interoperability is limited, as agreed soil health data standards are still emerging.

We can conclude that there is growing attention to soil ecosystem services and soil health from science, policy and the private sector. Many soil ESS and soil health frameworks are emerging, but

there is no consistent, soil-specific ESS-linked indicator system that works from EU scale down to the farm/parcel, that can, moreover, be used reliably in valuation and reward schemes, yet. Conceptual gaps, monitoring gaps, economic gaps and technical gaps all contribute to this. National and EU monitoring systems can provide backbone data, but are not ready yet to support robust, multi-service ESS monitoring at field or farm scale for operational payment or reward schemes.

## Key findings

- ESS concepts and classification systems are fragmented and not soil-specific; CICES v5.1 is widely used in Europe but complex and not fully adapted to soil, which weakens consistency across studies and policies;
- There is persistent confusion between soil functions/processes and soil ESS, which undermines indicator design and the credibility of payment schemes;
- National and EU monitoring mainly track chemical and physical indicators (SOC, nutrients, pH, bulk density, contaminants); biological and explicit ESS indicators are rarely monitored and poorly developed scientifically;
- Data harmonization across countries is limited; differing sampling designs, methods and data formats reduce comparability and reuse of soil data;
- The Soil Monitoring Law (Directive (EU) 2025/2360, 2025) sets common indicators and "healthy soil" criteria, but does not yet offer operational, quantitative links from these indicators to ESS metrics at farm/parcel level;
- Economic incentives for soil-related ESS are growing, with 92 programmes identified and 48 business models, but are heavily concentrated on carbon sequestration;
- Other soil-related ESS such as erosion control, flood control, pollination and climate resilience are rarely targeted compared with carbon storage, biodiversity, and water-related services (e.g. water quality, storage and supply);
- Schemes differ between activity-based systems and results-based systems. Activity-based systems reward farmers for implementing specific practices. Results-based systems reward farmers for achieving measured or modelled outcomes, such as an increase in soil carbon. Results-based schemes are gaining attention but require robust, affordable monitoring and can shift risk to farmers when results depend on external factors such as weather;
- There is an important difference between direct measurements and indirect indicators. Direct measurements, such as laboratory soil carbon tests, are more accurate but costly and difficult to repeat often. Indirect indicators, such as modelled estimates or satellite-based proxies, are cheaper and easier to scale up, but depend on assumptions and need local calibration to achieve acceptable accuracy. Many schemes mix both approaches, but methods are often only partly disclosed or have different ownership rights;
- Technologies for soil and ESS monitoring are diverse and advancing (soil scanners, in-situ sensors, drones, satellites), but many require local calibration and are constrained by cloud cover, crop effects, bare-soil requirements, and drone regulation;

- Data is scattered across platforms with uneven interoperability and ownership rights, so there is no common, practical data standard for soil health and soil-related ESS.

## Recommendations

- Agree on a practical, soil-specific ESS framework (for example, a defined soil subset of CICES) that clearly separates soil functions from ESS and is used consistently across EU and national initiatives;
- Extend national and EU monitoring systems with a core set of biological indicators and explicit soil-ESS indicators, and quantify how key soil indicators (e.g. SOC) translate into specific ESS at farm and field level;
- Establish a representative network of benchmark farms where different indicators and key management data are monitored using standardised protocols. Use these sites to calibrate and validate models, evaluate frameworks, test indicators, and provide transparent benchmarks for farmers and schemes;Broaden business models beyond carbon storage by designing pilots that reward additional soil-related ESS such as erosion control, water regulation, pollination and climate resilience, with fully documented monitoring methods and open, reviewable indicator sets;
- Clearly define when direct measurements are required and when model-based or proxy/indirect indicators are acceptable. Establish transparent uncertainty ranges and calibration/validation protocols to maintain credibility and trust while enabling scalability;
- When designing payment schemes, explicitly choose between activity-based and results-based approaches, or combine them carefully. Hybrid systems that reward both good practices and verified outcomes - may offer a pragmatic pathway, reduce risk while keep environmental integrity and trust;
- Invest in calibration datasets, open protocols and data standards so that sensor data, satellite products and farm records can be combined across platforms and countries/initiatives for soil-ESS assessment.

# Samenvatting

Dit rapport geeft een overzicht van de huidige stand van zaken rond concepten voor bodemgerelateerde ecosysteemdiensten (ESS), monitoringsystemen, verdienmodellen en monitoringtechnologieën, en onderzoekt of deze kunnen ingezet worden ter ondersteuning van beloningsmechanismen voor landbouwers en landbeheerders.

Het concept van ESS wordt veel gebruikt in beleid en onderzoek, maar definities en classificaties zijn nog steeds niet geharmoniseerd. Verschillende ESS-systemen bestaan naast elkaar. Ze maken gebruik van verschillende terminologie, hebben een andere classificatiestructuur en bodems zijn vaak verborgen binnen bredere categorieën. CICES v5.1 is het meest gedetailleerde en meest gebruikte raamwerk in Europa, maar is complex en niet volledig aangepast aan bodemaspecten. Er is voortdurende verwarring tussen bodemfuncties of -processen (wat bodems doen) en bodem-ecosysteemdiensten (de voordelen voor mensen die uit deze functies voortkomen). Recent werk, probeert dit op te lossen door subsets van CICES-klassen te definiëren die duidelijk bodem- en beheergerelateerd zijn en door shortlists voor te stellen voor meer gestandaardiseerde beoordelingen, maar dit wordt nog niet op grote schaal toegepast.

Er bestaan talrijke bodemmonitoringssystemen, maar deze zijn meestal niet geschikt om de ESS van de bodem rechtstreeks te monitoren. Veel initiatieven op EU- en nationaal niveau volgen vooral standaard bodemkwaliteitsindicatoren: bodemorganische koolstof (SOC), macro- en micronutriënten, pH, kationenuitwisselingscapaciteit, baseverzadiging, textuur, bulkdichtheid en contaminatie. Daarnaast worden biologische indicatoren en expliciete ESS-indicatoren zelden meegenomen. Analyse- en bemonsteringsmethodes verschillen tussen landen, wat gegevensuitwisseling en vergelijking bemoeilijkt. De nieuwe EU-richtlijn inzake bodemmonitoring (Richtlijn (EU) 2025/2360, 2025)) stelt gemeenschappelijke indicatoren en criteria voor voor “gezonde bodems” tegen 2050 en legt expliciet een link tussen bodemtoestand en meerdere ESS, maar specificeert nog geen robuuste, kwantitatieve relaties tussen deze indicatoren en concrete methodes om ESS te meten op bedrijfsniveau.

Hiernaast bestaan er reeds talrijke beloningssystemen voor ESS. We identificeerden 92 programma’s, waarvan 48 kunnen worden beschouwd als verdienmodellen met ten minste gedeeltelijke private of marktgebaseerde financiering. De meeste hiervan werken met directe betalingen volgens het *Payment for Ecosystem Services*-principe, 4 gebruiken labels of certificering en 1 gebruikt financieel advies als belangrijkste prikkel. Over de 92 programma’s heen wordt koolstofvastlegging 75 keer genoemd, biodiversiteit 62 keer en watergerelateerde diensten 60 keer, terwijl erosiebestrijding, bescherming tegen overstroming, bestuiving en klimaatrobuustheid veel minder vaak genoemd worden. Monitoring in deze systemen steunt vooral op bodemeigenschappen en landbouwpraktijken, met in het bijzonder bodemorganische stof. We stelden een toenemende verschuiving naar meer kwantitatieve en resultaatgerichte monitoring vast, vooral in private programma’s. Veel programma’s, vooral koolstoflandbouwinitiatieven, maken hun indicatoren en methoden slechts gedeeltelijk openbaar, wat de transparantie en vergelijkbaarheid beperkt.

Technologieën om bodemgerelateerde ESS te monitoren werden geïnventariseerd en de voor- en nadelen van de verschillende technieken werden beschreven. Het betreft tractor- en handbediende bodemscanners, in-situ bodemsensoren, informatie verkregen via remote sensing met drones of satellieten en dataplatforms. Scanners, sensoren en remote sensingbeelden meten zowel directe als indirecte bodemparameters. In de praktijk wordt het gebruik ervan beperkt door de noodzaak van lokale kalibratie en het feit dat veel methoden een niet-begroeide bodem vereisen, wat steeds minder vaak voorkomt door het toenemende gebruik van bodembedekkers en het behoud van gewasresten. Bovendien wordt het gebruik van optische satellieten sterk beperkt door bewolking in Europa en zijn de voorschriften voor drones streng. Dataplatforms en datauitwisselingssystemen zoals DjustConnect winnen aan belang. Datasets blijven echter versnipperd over verschillende private platforms. Hoewel er API's beschikbaar zijn, is echte interoperabiliteit beperkt, aangezien standaarden voor bodemgezondheidsgegevens nog in ontwikkeling zijn.

We kunnen concluderen dat er vanuit het onderzoek, het beleid en de private sector steeds meer aandacht is voor bodemecosysteemdiensten en bodemgezondheid. Er ontstaan veel kaders voor het meten en classificeren van bodem-ESS en bodemgezondheid, maar er is nog geen consistent, bodemspecifiek ESS-gerelateerd indicatorsysteem dat werkt van EU-schaal tot aan het niveau van een landbouwbedrijf/perceel, dat bovendien betrouwbaar kan worden gebruikt in beloningssystemen. Conceptuele hiaten, hiaten in de monitoring, economische hiaten en technische hiaten dragen hier allemaal aan bij. Nationale en EU-monitoringssystemen kunnen basisgegevens leveren, maar zijn nog niet klaar om robuuste, *multiservice* ESS-monitoring op veld- of boerderijschaal te ondersteunen voor operationele beloningsregelingen.

## Belangrijkste bevindingen

- ESS-concepten en -classificatiesystemen zijn niet geharmoniseerd en niet bodemspecifiek; CICES v5.1 wordt veel gebruikt in Europa maar het is een complex systeem en niet volledig afgestemd op bodem, wat de consistentie tussen studies en beleid die hiervan gebruik maken verzwakt;
- Er blijft verwarring tussen bodemfuncties/-processen en bodem-ESS, wat het ontwerp van indicatoren en de geloofwaardigheid van beloningsprogramma's ondermijnt;
- Nationale en Europese monitoringsystemen gebruiken vooral chemische en fysische indicatoren (SOC, nutriënten, pH, bulkdichtheid, contaminatie); biologische en expliciete ESS-indicatoren worden zelden gemonitord en zijn wetenschappelijk nog weinig ontwikkeld;
- Er is beperkte harmonisatie van bodemdata tussen landen; verschillende methodes van bemonsteren en bodemanalyse en verschillende gegevensformaten verminderen vergelijkbaarheid en hergebruik van bodemdata;
- De Soil Monitoring Law (Directive (EU) 2025/2360, 2025) stelt gemeenschappelijke indicatoren en criteria voor "gezonde bodem" voor, maar biedt nog geen operationele, kwantitatieve koppelingen van deze indicatoren aan ESS op bedrijfs- of perceelniveau;

- Het aantal programma's die bodemgerelateerde ESS beloont neemt toe (we identificeerden 92 programma's en 48 verdienmodellen), maar de focus ligt sterk op koolstofvastlegging;
- Bodemgerelateerde ESS, zoals erosiebestrijding, het beperken van het overstromingsrisico, bestuiving en klimaatrobuustheid, komen minder aan bod dan koolstofopbouw, biodiversiteit en watergerelateerde diensten (waterkwaliteit, -opslag en -aanvoer);
- Er is een verschil tussen op activiteiten gebaseerde systemen en op resultaten gebaseerde systemen. Op activiteiten gebaseerde systemen belonen landbouwers voor het toepassen van specifieke praktijken. Op resultaten gebaseerde systemen belonen landbouwesr voor het behalen van meetbare resultaten, zoals een toename van koolstof in de bodem. Op resultaten gebaseerde systemen krijgen steeds meer aandacht, maar vereisen een robuuste, betaalbare monitoring en kunnen het risico naar de landbouwers verschuiven wanneer de resultaten afhankelijk zijn van externe factoren zoals het weer;
- Er is een belangrijk verschil tussen directe metingen en indirecte indicatoren. Directe metingen, zoals laboratoriumtests voor koolstof in de bodem, zijn nauwkeuriger, maar duur en moeilijk vaak te herhalen. Indirecte indicatoren, zoals gemodelleerde schattingen of satellietgebaseerde proxies, zijn goedkoper en gemakkelijker op te schalen, maar zijn afhankelijk van aannames en moeten lokaal worden gekalibreerd om een aanvaardbare nauwkeurigheid te bereiken. Veel programma's combineren beide benaderingen, maar de monitoringsmethoden worden vaak slechts gedeeltelijk openbaar gemaakt of zijn eigendom van de ontwikkelaar;
- Technologieën voor bodem- en ESS-monitoring zijn divers en ontwikkelen zich snel (bodemscanners, bodemsensoren, beelden vanop drones of satellieten), maar vereisen vaak lokale kalibratie en worden beperkt door bewolking, gewaseffecten, nood aan onbedekte bodems en wetgeving;
- Data staan verspreid over verschillende private dataplatformen met wisselende interoperabiliteit, en er bestaat nog geen gemeenschappelijke, praktische datastandaard voor bodemgezondheid en bodemgerelateerde ESS.

### Aanbevelingen

- Ontwikkel een praktisch systeem voor het classificeren van bodemspecifieke ESS (bijvoorbeeld een duidelijk gedefinieerde bodemsubset van CICES), dat bodemfuncties duidelijk scheidt van ESS en consequent wordt gebruikt in Europese en nationale/lokale initiatieven;
- Breid nationale en EU-monitoringsystemen uit met een kernset biologische indicatoren en expliciete bodem-ESS-indicatoren, en kwantificeer hoe belangrijke bodemindicatoren (zoals SOC) zich vertalen naar specifieke ESS op bedrijfs- en perceelniveau;
- Richt een representatief netwerk van *benchmark*bedrijven op waar verschillende indicatoren en belangrijke gegevens over bodembeheer worden gemonitord met gestandaardiseerde protocollen. Gebruik deze locaties om modellen te kalibreren en te

valideren, indicatoren te testen en transparante referenties te bieden voor landbouwers en beloningsprogramma's;

- Verbreed de verdienmodellen voorbij koolstof door pilots te ontwerpen die ook andere bodemgerelateerde ESS belonen, zoals erosiebestrijding, waterregulatie, bestuiving en klimaatrobuustheid, met volledig gedocumenteerde monitoringsmethoden en open, toetsbare indicatorensets;
- Definieer duidelijk wanneer directe metingen vereist zijn en wanneer op modellen gebaseerde of proxy/indirecte indicatoren aanvaardbaar zijn. Stel transparante onzekerheidsmarges en kalibratie-/validatieprotocollen vast om de geloofwaardigheid en het vertrouwen te behouden en tegelijkertijd schaalbaarheid mogelijk te maken;
- Kies bij het ontwerpen van beloningsprogramma's expliciet tussen een op activiteiten gebaseerde en een op resultaten gebaseerde aanpak, of combineer deze zorgvuldig. Hybride systemen die zowel goede praktijken als geverifieerde resultaten belonen kunnen een pragmatische oplossing bieden, risico's verminderen en tegelijkertijd het vertrouwen behouden.
- Investeer in kalibratiedatasets, open protocollen en datastandaarden zodat sensordata, satellietproducten en bedrijfsgegevens gecombineerd kunnen worden over platformen en landen/initiatieven heen voor de beoordeling van bodem-ESS.

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# 1. Introduction

## 1.1 Purpose of the report (EN)

This report is part of the SoilValues project (Task 1.1) and focuses on establishing a multidisciplinary knowledge base and mapping scientific knowledge on the ecosystems services (ESS) concept, as well as on technologies and data support systems for monitoring, reporting and verifying soil- and agricultural management-related ESS and soil health.

Apart from delivering marketable products, agricultural practices also have the potential to contribute to other soil ESS. However, land managers generally have little incentive to invest in healthy soils, as they cannot sufficiently capture the value generated by these ecosystem services. The SoilValues project aims to improve the conditions for developing successful soil health business models. These are models in which land managers make production decisions that result in higher levels of soil-related ESS and in which they are paid for the non-marketed services they generate.

In order to design and implement an incentive scheme or business model for the different soil- and agricultural management-related ESS provided by a farm/agricultural parcel there are several steps including the identification of the ESS that are potentially provided by the implemented practices and that actors are willing to pay for, the establishment of a scheme and its rules and guiding principles andthe monitoring, reporting and verification (of the ESS).

This report starts in Chapter 2 Mapping scientific knowledge on (soil) ecosystems services with a state-of-the art of scientific knowledge on what are soil ecosystem services, how soil health is defined and how these ESS and soil health indicators could be monitored. In Chapter 3 Business Models and soil health programs, existing business models for soil health and soil ecosystem services are inventoried, including how they monitor. Cost-efficient monitoring, reporting and verification (MRV) is crucial for business models that can be easily upscaled, therefore, Chapter 4 Technologies for Measurement and Management provides an inventory of current monitoring technologies, sensor and data support systems that could be included in the MRV process.

This report aims to provide a catalogue of options for the SoilValues communities of practices and testing grounds to make informed decisions. Additionally, the report serves to inform subsequent tasks and work packages by feeding them with valuable insights and information on the topic of mapping, monitoring, and valuating ESS.

## 1.2 Doel van het rapport (NL)

Dit rapport beschrijft de bevindingen en resultaten van activiteit T1.1 van het SoilValues-project. Het richt zich op het uitbouwen van een multidisciplinaire kennisbasis en het in kaart brengen van wetenschappelijke kennis over het ecosysteemdienstenconcept (ESS), evenals over technologieën en datasystemen voor het monitoren, rapporteren en verifiëren van bodem- en landbouwbeheergerelateerde ecosysteemdiensten (BESD) en bodemgezondheid.

Naast het leveren van producten voor de markt, kunnen landbouwpraktijken ook bijdragen aan andere BESD. Toch hebben landbouwers en andere landbeheerders meestal weinig stimulans om te investeren in gezonde bodems, omdat ze de waarde die deze ecosysteemdiensten opleveren, niet voldoende kunnen verzilveren. Het SoilValues-project wil bijdragen aan de voorwaarden voor het ontwikkelen van succesvolle verdienmodellen rond bodemgezondheid. Dat zijn modellen waarbij landbeheerders productiebeslissingen nemen die leiden tot hogere niveaus van BESD, en waarbij ze betaald worden voor de niet-vermarktbare diensten die ze leveren.

Om een verdienmodel uit te werken en toe te passen voor de verschillende aan bodem- en landbeheergerelateerde ESS, die door een landbouwbedrijf of perceel worden geleverd, zijn er verschillende stappen nodig waaronder het identificeren van de mogelijke ESS die potentieel worden geleverd door de geïmplementeerde praktijken en waarvoor actoren bereid zijn te betalen, het opzetten van een regeling en de bijbehorende regels en leidende principes, en het monitoren, rapporteren en verifiëren (van de ESS). Dit rapport begint in hoofdstuk 2 In kaart brengen van wetenschappelijke kennis over BESD met een overzicht van de huidige stand van zaken in de wetenschap over wat BESD zijn, hoe bodemgezondheid wordt gedefinieerd en hoe deze ESS- en bodemgezondheidsindicatoren kunnen worden gemonitord. In hoofdstuk 3, Bedrijfsmodellen en bodemgezondheidsprogramma's, worden bestaande bedrijfsmodellen voor bodemgezondheid en BESD geïnventariseerd, inclusief hoe ze worden gemonitord. Kostenefficiënte monitoring, rapportage en verificatie (MRV) is cruciaal voor bedrijfsmodellen die gemakkelijk kunnen worden opgeschaald. Daarom biedt hoofdstuk 4, Technologieën voor meting en beheer, een inventarisatie van de huidige monitoringtechnologieën, sensoren en gegevensondersteunende systemen die in het MRV-proces kunnen worden opgenomen.

Dit rapport heeft tot doel een catalogus van opties te bieden voor de SoilValues-praktijkgemeenschappen en proefprojecten, zodat zij weloverwogen beslissingen kunnen nemen. Daarnaast dient het rapport als basis voor volgende taken en werkpakketten door hen te voorzien van waardevolle inzichten en informatie over het in kaart brengen, monitoren en waarderen van ESS.

# 2. Mapping scientific knowledge on (soil) ecosystems services

## 2.1 Defining ecosystem services, classification systems, soil-related ecosystem services and soil health

### 2.1.1 Definitions of ecosystem services

Several definitions and philosophies exist in literature regarding the ESS concept summarized by Nahlik et al. (2012). The primary disagreement among them is whether ESS are directly linked to the benefits provided by ecosystems or if they are associated with the attributes of ecosystems that ultimately lead to these benefits. Nevertheless, one resemblance in all these perspectives is that ESS are connected to human benefits (Nahlik et al., 2012).

The Millennium Ecosystem Assessment (MEA) (Millennium Ecosystem Assessment, 2003, 2005) defines ESS as "the benefits that people obtain from ecosystems". The Economics of Ecosystems and Biodiversity initiative (TEEB, 2008) defines ESS as "the direct and indirect contributions of ecosystems to human well-being". SOILS4EU (van der Meulen & Maring, 2018) extended this definition to "the goods and services provided by ecosystems that directly and indirectly contribute to human well-being" to refer to the essential aspect of the ESS concept, that it is an anthropocentric approach.

### 2.1.2 History of the ecosystem services concept

Throughout history, humanity has relied on the natural environment for its survival and prosperity. The myriad benefits provided by ecosystems, ranging from clean air and water to the provision of food and natural resources, have sustained human societies for millennia. However, it was not until the latter half of the 20$^{th}$ century that the true value of these services became a subject of intense scientific scrutiny and public awareness (Westman, 1977). This growing recognition led to the emergence of the concept of ESS, with the specific term to originate in the early 1980s (Ehrlich & Ehrlich, 1981) which revolutionized our understanding of the intricate relationship between ecosystems and human well-being. The gaining prominence within the scientific community and subsequently spreading into policy and public discourse came in the late 90s with the Nature paper of Costanza et al. (1997) about the values of the worlds ESS which brought the concept to the surface and center of attention while causing controversial criticism highlighting the need for additional research and attention on the topic. It was a realization that ecosystems are not static entities, but dynamic providers of essential goods and services that sustain life on earth, emphasizing the integral role of nature in supporting our daily lives and economic systems. A detailed history of the ESS concept focused on its economic roots is presented by Gómez-Baggethun et al. (2010) and in the economic and ecological roots by Braat &

de Groot (2012). Chaudhary et al. (2015) reviewed the evolution of the ESS concept and traced the rapid growth of ESS across academic disciplines and amongst organizations at the boundary of science and policy. More recently, Costanza et al. (2017) summarized the progress made in understanding and implementing the concept of ESS over the past two decades but also evaluated the advancements, challenges, and future directions in the field.

The evolution of the ESS concept has been driven by various influential developments. One milestone was the launch of the **MEA** in 2001, and the MEA comprehensive evaluation of global ESS published in 2005, emphasized the multifaceted nature of these services. Later in 2008 the publication of the landmark book "The Economics of Ecosystems and Biodiversity" **(TEEB) report** (TEEB, 2008) which shed light on the economic value of ESS and highlighted the potential socioeconomic consequences of their degradation, increased interest from economists, policymakers, and conservationists, spurring further research and discussion on valuing and managing ESS. Also, the establishment of global partnerships and platforms such us the **Ecosystem Services partnership** in 2008 and the **Intergovernmental Science-Policy Platform on biodiversity and Ecosystem Services** in 2012 enhanced the science, policy and practice of the ESS.

### 2.1.3 Ecosystem services classification systems

All the different reports and initiatives emphasize the multifaceted nature of the ESS. To better understand and manage these services, classification systems have been developed as valuable tools. By providing a structured framework categorizing and describing them, these systems enable a more systematic approach to understanding, measuring, valuing, mapping, and managing ESS. Classification systems enhance our ability to communicate the value of nature to society and analyze the benefits derived from ecosystems, increase awareness, facilitate informed decision-making processes, and design policies. The ESS classification systems have important implications for policy and management. These systems provide a common language and analytical framework for integrating ESS into decision-making processes. By quantifying and mapping services, policymakers can better understand the spatial distribution and value of ESS and take more informed decisions. The European Biodiversity Strategy of 2020 (European Commission, 2011) recognized ESS mapping as a strategic action, and the Member States were stimulated to map and assess the condition of ecosystems and their services.

Various classification systems have been proposed in literature, each with its own unique features and frameworks which offer different perspectives and criteria for classifying ESS, to serve research needs and policy contexts. Costanza et al. (1997) identified 17 ESS in a general list, while newer classification systems group the several ESS in broader categories. The **MEA typology**

(Millennium Ecosystem Assessment, 2003, 2005) provides a simplified yet comprehensive overview and is widely used for ESS assessments. It categorizes the ESS into four broad categories: provisioning services (e.g., food, water), regulating services (e.g., climate regulation, water purification), cultural services (e.g., recreational, and aesthetic value), and supporting services (e.g., nutrient cycling, soil formation). It focuses on the benefits that ecosystems provide to humans, with an emphasis on human well-being and the socioeconomic aspects. The MEA typology has been adopted by various organizations and initiatives, making it a common reference point in the field of ESS. Nevertheless, the MEA typology's simplicity can limit its ability to capture the full complexity of ESS. While the MEA typology acknowledges cultural services, it may not fully capture the cultural dimensions associated with these services, potentially leading to their undervaluation.

The **TEEB classification** (de Groot et al., 2010), which focuses on the economic aspects of ESS, emphasizing the valuation and incorporation of monetary values into decision-making processes, adopted the MEA categories apart from the "supporting services", which were replaced by the "habitat or supporting services."

The most recent classification system, widely used in Europe (e.g., EEA, JRC)), i.e., the **Common International Classification of Ecosystem Services (CICES)** (Haines-Young & Potschin, 2018) categorizes the ESS into three broad categories: "provisioning", "regulation & maintenance" and "cultural" services. The "supporting services" category is not included because of the anthropocentric definition of ESS followed, but several services form this category are included in the "regulation and maintenance services" category (Paul et al., 2021). In CICES, ESS are defined as the contributions that ecosystems make to human well-being and are distinct from the goods and benefits that people subsequently derive from them. Thus, in CICES v5.1 the definition of each service identifies both the purposes or uses that people have for the different kinds of ESS and the particular ecosystem attributes or behaviors that support them.

CICES takes a more comprehensive approach, using a detailed hierarchical framework, organizing ESS into a multi-level classification system that covers the wide range and complexity of ESS, and allows for a more comprehensive and detailed analysis. Because of this multi-level classification, the CICES framework can be used in different scales and ecosystems, facilitating specific research and policy needs. On the other hand, the detailed structure of CICES can make it more complex and technically demanding to apply compared to simpler classification systems. CICES is not intended to replace the other classification systems, but to allow easy translation between them and in order to help people navigate between these different systems.

All classification systems have advantages and disadvantages, and the choice among them depends on the specific research or policy objectives, the level of detail required, and the context in which they are applied. Some of the classification systems and their references are included in Table 2-1.

*Table 2-1: Different ecosystems classification systems*

| Name of the classification system | Source |
|---|---|
| CICES - Common International Classification of Ecosystem Services | https://cices.eu/ |
| INCA - Accounting for ESS in the European Union | https://ec.europa.eu/eurostat/web/products-statistical-reports/-/ks-ft-20-002 |
| MEA - Millennium Ecosystem Assessment Framework | https://www.millenniumassessment.org/en/index.html |
| TEEB - The Economics of Ecosystems and Biodiversity classification | https://teebweb.org/ |
| IPBES - Intergovernmental Science-Policy Platform on biodiversity and Ecosystem Services assessment | https://www.ipbes.net/, (Díaz et al., 2018; IPBES, 2019) |
| National Ecosystem Assessments (e.g., UK NEA, Ethiopia NEA) | https://www.ecosystemassessments.net/assessment-process/what-are-neas/ |
| NESCS - National Ecosystem Services Classification System (USA) | https://www.epa.gov/eco-research/final-ecosystem-goods-and-services-fegs |

The different ESS categorized in different classification schemes are shown in Table 2-2.

*Table 2-2: The different ecosystem services categories appear in different classification systems. The different ESS from each system were connected based on detailed information for each ESS category in the corresponding references, the CICES v5.1 spreadsheet, the Classifying Ecosystem Services |HUGIN OpenNESS (Haines-Young & Potschin, 2016) tool and experts' opinion.*

| Nature paper (Costanza et al., 1997) | MEA (Millennium Ecosystem Assessment, 2003, 2005) | TEEB (de Groot et al., 2010) | IPBES (Díaz et al., 2018; IPBES, 2019) |
|---|---|---|---|
| Gas regulation | Air quality regulation | Air quality regulation | 3. Regulation of air quality |
| Climate regulation | Atmospheric regulation | Climate regulation | 4. Regulation of climate |

| | | | |
|---|---|---|---|
| Disturbance regulation | Natural hazard regulation | Regulation of extreme events | 9. Regulation of hazards and extreme events |
| Water regulation | Water regulation | Regulation of water flows | 6. Regulation of freshwater quantity, location and timing |
| Water supply | Water | Water | 7. Regulation of freshwater and coastal water quality |
| Waste treatment | Water purification and water treatment, | Waste treatment (water purification) | |
| Erosion control & sediment retention | Erosion regulation | Erosion prevention | 8. Formation, protection and decontamination of soils and sediments |
| Soil formation | Soil formation | Maintenance of soil fertility (inc. soil formation) and nutrient cycling | |
| Nutrient cycling | | | |
| Pollination | Pollination | Pollination | 2. Pollination and dispersal of seeds and other propagules |
| Biological control | Pest regulation | Biological control | 10. Regulation of detrimental organisms and biological processes |
| | Disease regulation | | |
| Refugia | | Maintenance of genetic diversity | 1. Habitat creation and maintenance |
| | | Maintenance of life cycles of migratory species | 18. Maintenance of options |
| Food production | Food | Food | 12. Food and feed |
| Raw materials | Fiber, Timber, Ornamental | Raw materials | 11. Energy |
| | | Ornamental resources | 13. Materials and assistance |
| Genetic resources | Genetic materials | Genetic materials | 14. Medicinal, biochemical and genetic resources |
| | Biochemicals, natural medicines, pharmaceuticals | Medicinal resources | |
| Recreation | Recreation and ecotourism | Recreation and tourism | 16. Physical and psychological experiences |
| Cultural | Aesthetic values, Knowledge systems and educational values, cultural diversity | Inspiration for culture, art and design | |
| | | Information and cognitive development | 15. Learning and inspiration |
| | | Aesthetic information | 17. Supporting identities |

| | | | |
|---|---|---|---|
| | Spiritual and religious values | Spiritual experience | |
| | | | 5. Regulation of ocean acidification |

### 2.1.4 Need for consensus – Identification of soil- and agricultural management-related ecosystem services.

The drawback of having so many different classification systems is that they all approach the ESS concept in different ways, and so they are not always easy to compare. Despite the efforts and work the last years (e.g., CICES v5 included also the codes and names of the relevant other systems), or the tool to navigate within the different classification systems: Classifying Ecosystem Services |HUGIN OpenNESS (Haines-Young & Potschin, 2016), the problem of consensus in the ESS terminology is still existing (Nahlik et al., 2012; Paul et al., 2021). Apart from using different terminologies coming from the different classification systems, due to the multitude of definitions and the resulting uncertainty, the term "ecosystem service" has transformed into a broad expression encompassing anything within or derived from an ecosystem that benefits living organisms (Nahlik et al., 2012).

When it comes to soils, the term "ecosystem service" is used many times to refer to the soil functions or the soil processes, creating confusion and miscommunication. Soil ESS are ESS that depend on the functional processes and properties of the soil. A clear distinction is made between soil functions and soil ESS. Functions are the ecological processes that result in the supply of ESS, while services are the benefits that people obtain either directly or indirectly for the ecosystems (van der Meulen & Maring, 2018). Within the different classification lists of ESS, it is recognized that not all services are directly applicable to soil or significantly influenced by agricultural management practices. Hence, here we aim to present the outcomes derived from a review of relevant literature, projects leading to the identification and selection of specific ESS that are pertinent to agricultural management and soil. By focusing on these specific services, we can gain valuable insights into the interplay between agricultural practices, soil management, and the provision of crucial ESS that are most impacted.

Recently, Paul et al. (2021), to support the standardization of soil-related ESS, used the detailed and hierarchical last version of the CICES to compile two subsets of its classes, one set of soil-related ESS and another set of agricultural management-related ESS. These shortlists could aid in adopting a uniform method and potentially serve as assessment guidelines for evaluating impacts.

According to Soils4EU (van der Meulen & Maring, 2018), generally, a number of the soil ESS are often not considered in general ESS assessments or in soil ESS assessments and when analyzing

the impact of soil management practices on ESS, it is recommended to consider the entire list of soil ESS to prevent that less obvious aspects are overlooked. It is also important to consider the trade-offs between the potential supply, actual use, and future demand of multiple soil ESS. The use of one service may result in reduced capacity of another service. For example, increasing the area for forests while decreasing the area suitable for arable land, as a carbon farming measure, could lead to a trade-off between two ESS, carbon storage and food production.

### 2.1.5 Definitions of soil health

Soil health is a relatively recent concept that only gained traction in the 90s and early 2000s (Bünemann et al., 2018; Lehmann et al., 2020). Acton & Gregorich (1995) provided one of the earliest definitions of the term: "the soil's fitness to support crop growth without becoming degraded or otherwise harming the environment". Doran (2002) broadened the scope of the concept to "the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health." The trend of the term's meaning, as exemplified by the more recent definition of the US Department of Agriculture (i.e. "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans"), has been towards a concept in which the health of the environment, animals and humans are all connected by the soil's continued provision of vital ESS (Lehmann et al., 2020). The term is often used interchangeably with soil quality. However, Lehmann et al. (2020) makes the claim that the scope of soil health is broader, not limiting the focus to ESS with direct reference to human health (e.g. biomass production and water supply and regulation), but to also including ESS that reference a broader planetary health (e.g. biodiversity and carbon sequestration).

### 2.1.6 Need for valuation and rewarding for ecosystem services

ESS are now well recognized for their value (Gómez-Baggethun et al., 2010; van der Meulen & Maring, 2018). Economic valuation of soil ESS not only highlights their significance for human and societal well-being but also facilitates decision-making across various organizational levels concerning soil and land management, because it allows us to consider the full range of relevant effects. Often, many ESS refer to public goods, making their impact less obvious and direct. Since preferences for these services may not be well-defined, without valuation, their importance might be overlooked. Also, in many cases there are trade-offs between the different ESSs. By utilizing economic valuation, we gain a better understanding of the possible effects and trade-offs, leading to more informed decision-making.

Nevertheless, the (non-market) economic valuation of the different ESS is an area that still requires a lot of research since neither conceptually nor methodologically the existing approaches can cover the needs and developments of the ESS concept (Baveye et al., 2016; Jónsson & Davíðsdóttir, 2016; Robinson et al., 2014; van der Meulen & Maring, 2018). The economic valuation of ESS is based on the preferences the different stakeholders have for these services, and their value can be expressed on different scales, from qualitative to monetary. Several methods have been used for the economic valuation of the ESS depending on their nature and the purpose of the valuation. These methods can be either for non-market ESS (e.g., cost-based, revealed preference methods, stated preference methods) or for market ESS (most studies use market price proxies or cost-based methods to estimate the economic value of ESS). Brander et al. (2023), Jónsson & Davíðsdóttir (2016) and van der Meulen & Maring (2018) have reviewed and present the different (soil) ESS economic valuation methods (Figure 2-1) and several databases on ESS values exist like the Ecosystem Services Valuation Database (ESVD) (Brander et al., 2023; de Groot et al., 2012), which is a follow-up to the "The Economics of Ecosystems and Biodiversity" (TEEB database) (McVittie & Hussain, 2013), which contained over 1,300 data points from 267 case studies on monetary values of ESS across all biomes or the Eurostat values for different ESS from the "Aggregation of EU ecosystem service accounts" study that tests the feasibility of aggregating independently produced ESS accounts to the EU level (Vysna et al., 2021).

| Valuation Method | Acronym | Method Description |
|---|---|---|
| Choice Modelling (Choice Experiment) | CE | Ask survey respondents to make trade-offs between ecosystem services and other goods or income to elicit willingness to pay |
| Contingent Valuation | CV | Ask survey respondents to state their willingness to pay for an ecosystem service through surveys |
| Damage Cost Avoided | DC | Estimated damage avoided due to ecosystem service |
| Defensive Expenditure | DE | Expenditure on protection of ecosystem services |
| Group Valuation (Participatory Valuation) | GV | Ask groups of stakeholders to state their willingness to pay for an ecosystem service through group discussion process |
| Hedonic Pricing | HP | Estimated influence of environmental characteristics on price of marketed goods |
| Input-Output Modelling | IO | Quantifies interdependencies between economic sectors to measure impacts of changes in one sector to other sectors in the economy. Ecosystems can be seen as distinct sectors. |
| Market Prices (Gross Revenue) | MP | Prices for ecosystem services that are directly observed in markets |
| Net Factor Income (Residual Value) | FI | Revenue from sales of ecosystem-related good minus cost of other inputs |
| Opportunity Cost | OC | The next highest valued use of the resources used to produce an ecosystem service |
| Production Function | PF | Statistical estimation of production function for a marketed good including an ES input |
| Public Pricing | PP | Public expenditure or monetary incentives (taxes/subsidies) for ES as an indicator of value |
| Replacement Cost | RC | Estimated cost of replacing an ES with a man-made service |
| Restoration Cost | RT | Estimated cost of restoring degraded ecosystems to ensure provision of an ecosystem service |
| Social Cost of Carbon | SC | Monetary value of damages caused by emitting one tonne of $CO_2$ in a given year. The social cost of carbon (SCC) therefore also represents the value of damages avoided for a tonne reduction in emissions. |
| Travel Cost | TC | Estimated demand for ecosystem recreation sites using data on travel costs and visit rates |
| Value Transfer (Benefits Transfer) | VT | Estimate of the ecosystem service value at a "policy site" using existing information from different "study site(s)". |
| Other | OT | Other valuation methods |

*Figure 2-1: List and description of ecosystem services valuation methods (Brander et al., 2018)*

## 2.2 Monitoring systems and indicators for mapping and measuring soil health and ecosystem services

### 2.2.1 Results of past and ongoing (EU) projects on indicators, proxies, and models for soil health and ecosystem services

The deliverable **D1.2 of the Soils4EU** (van der Meulen & Maring, 2018) in collaboration with the Working Group on Mapping and Assessment on Ecosystems and their Services (JRC's MAES WG) provides the most comprehensive review and state of the art on the topic of mapping and assessment of the soil ESS. Following the framework of the MAES WG, the first step when mapping and assessing ecosystems and their services starts with mapping the ecosystems, and the second step is to assess their physical chemical and biological quality and conditions as this determines their capacity to yield and provide services. It also shows that the different soil pressures influence the condition of the ecosystem and thus the ability to provide the different services (Figure 2-2).

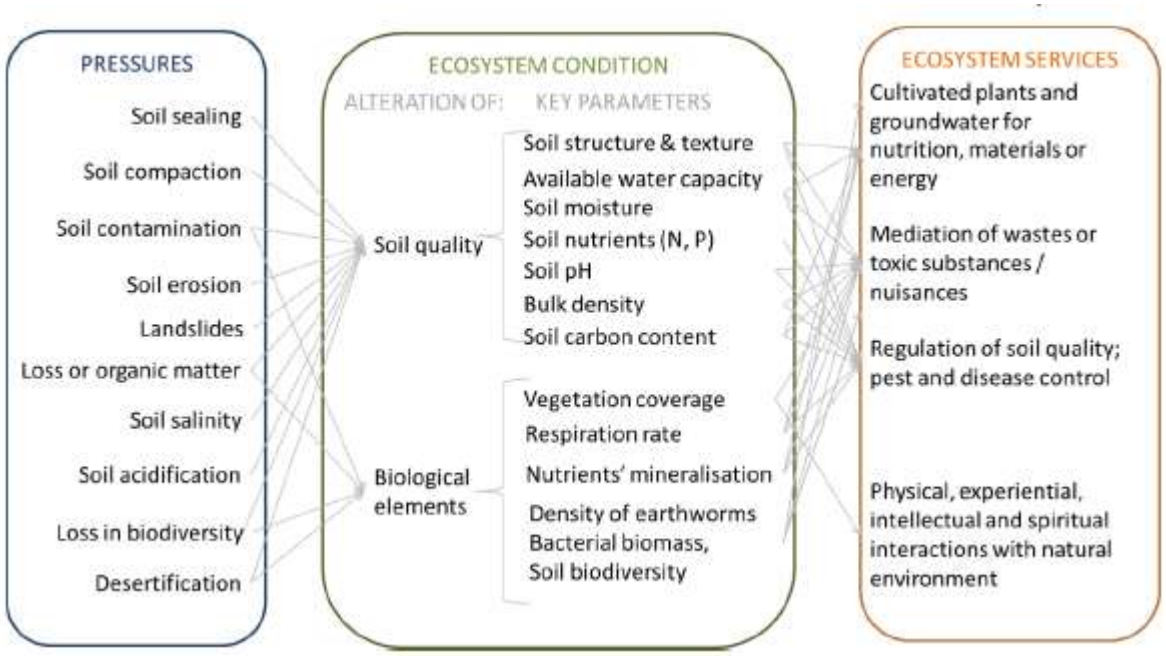



*Figure 2-2: This figure explains how the delivery of soil ecosystem services depends on ecosystem condition, which in turn is influenced by soil pressures (Developed by JRC's MAES Soil working group, 2017)*

In the report the CICES classification system is also used together with the simplified names of the different soil-related ESS, considered as well as the functional processes and properties that each ESS provides (see Table 3.1 in the original deliverable - not included in this report). In a second step for each ESS the available indicators to measure the ecosystem condition or to quantity an ESS were suggested (Figure 2-3, Figure 2-4, Figure 2-5).

| Ecosystem service | | | Indicator frame | | |
|---|---|---|---|---|---|
| Ecosystem Service | CICES class | CICES class type | Indicator [unit] & Strength of indicator | Supply or Use | Relevant spatial extent | Availability of data |
| Biochemical and pharmaceuticals (1) | *No class provided in CICES (CICES Division= Materials)* | *No class type provided in CICES* | ○ Raw materials for medicines [...] | S | Regional | European data for potential and use, as well as the role of soil are not found |
| Food, wood and fibre (1) | Cultivated terrestrial plants (incl. fungi, algae ) grown for nutritional purposes or as a source of energy; Fibres and other materials from cultivated pants fungi, algae and bacteria for direct use or processing. | Crops by amount, type | ● Surface area of organic crops [ha]<br>● Yields (ton/ha)<br>● Forest biomass stock (tons) | S | Regional | Data on production are available on European scale |
| Fresh water(1) | Ground (and subsurface) water for drinking or non-drinking purposes | By amount, type, source | ● Water retention index [dimensionless, between 0-10]<br>● Water abstraction ($m^3$ /yr) | S<br><br><br><br>U | Regional<br><br><br><br>Regional | There are data on water retention and water abstraction available on European scale |
| Carrying capacity for infrastructure, buildings and animals [support of animals and infrastructure][carrier function] (1) | *No class provided in CICES* | *No class type provided in CICES* | ● Suitability classes for building [-] | S | Local | There are no European data found but regional or national data may be used at the local level |
| Raw materials (1) | Mineral substances used for nutritional or material purposes or as energy source | Amount by type | ● Raw material extraction (tons/yr) | S | Regional | Current EU-covering projects did not yet deliver data on potential delivery or actual flow. |
| Thermal energy (1) | Ground water (and subsurface) used as an energy source; Geothermal | By amount & source, amount by type | ● Suitability classes for ATES [-]<br>● Demand based on above ground land use [PJ] | S<br><br>U | Local<br><br>Local | There are indicative data on suitability and demand on European scale |

*Figure 2-3: Indicator frame for provisioning soil ESS (Soils4EU, (van der Meulen & Maring, 2018))*

| Ecosystem service | | | Indicator frame | | | |
|---|---|---|---|---|---|---|
| Ecosystem Service | CICES class | CICES class type | Indicator [unit] & Strength of indicator | Supply or Use | Relevant spatial extent | Availability of data |
| Water purification and soil contamination reduction (1) | Bio-remediation by micro-organisms, algae, plants, and animals; Filtration /sequestration /storage/accumulation by micro-organisms, algae, plants, and animals; Mediation of waste toxics and other nuisances by non-living processes | By type of living system or by waste or substance type; amount by type | ● Nitrogen removal [dimensionless scale of 1-5]<br>● Concentration of pollutants in soil (mg/kg) | S<br><br>U | Regional<br><br>Local | No EU-wide data found |
| Water regulation (1) | Hydrological cycle and water flow regulation (including flood control and coastal protection); | By depth/volumes | ● Retention capacity of water in soils [dimensionless, between 0-10] | S | Regional | No EU-wide data found |
| Pest and disease control (2) | Pest control (including invasive species); Disease control | By reduction in incidence, risk, area protected | ○ For agricultural land: density of hedgerows (m / ha) | S | Regional | No European maps on biological control of pests and diseases. European map of threats to soil biodiversity may be relevant for future changes in soil biodiversity as indictor for pest and disease control |
| Carbon Sequestration (1) | Weathering processes and Decomposition and fixing processes and their effect on soil quality | By amount/concentration and source | ○ Carbon Sequestration [ton/ha/yr]<br>● Net ecosystem productivity | S<br><br>S | Regional<br><br>Regional | insufficient EU-wide data found.<br>C storage in forests are available, but not for other land uses (storage per unit of area) |
| Regulation of greenhouse gasses (2) | Regulation of chemical composition of atmosphere and oceans | By contribution of type of living system to amount, concentration and climatic parameter | | | | |
| Regulation of local climate/temperature (2) | Regulation of temperature and humidity, including ventilation and transpiration | By contribution of type of living system to amount, concentration and climatic parameter | ● Water retention index if applied at the scale of e.g. a city<br>● Uncovered soil | U<br><br>U | Local<br><br>Local | Data on a local scale might be available |
| Noise abatement (2) | Noise attenuation | By type of living system | ● Leaf Area Index + distance to roads (m) | S | Local | data provision on local level |
| Air quality regulation (2) | Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals; Mediation of waste toxics and other nuisances by non-living processes | By type of living system or by water or substance type; amount by type | ● Pollutants removed by vegetation (in leaves, stems | S | Local | data provision on local level |

*Figure 2-4: Indicator frame for regulation and maintenance soil ESS (Soils4EU,* (van der Meulen & Maring, 2018)*)*

| Ecosystem service | | | Indicator frame | | | |
|---|---|---|---|---|---|---|
| Ecosystem Service | CICES class | CICES class type | Indicator [unit] & Strength of indicator | Capacity or Demand | Relevant spatial extent | Availability of data |
| Recreation and tourism (2) | Characteristics of living systems that enable activities promoting health recuperation or enjoyment through active or immersive interactions; or through passive or observational interactions; natural abiotic characteristics of nature that enable active or passive and experiential interactions | By type of living system or environmental setting; amount by type | • Number of visitors<br>• Distribution of sites | U<br>S | Local<br>Regional | No data on European scale |
| Knowledge/scientific research, Cultural heritage and education (1) | Characteristics of living systems that: enable scientific investigation or the creation of traditional ecological knowledge; enable education and training; are resonant in terms of culture or heritage; enable aesthetic experiences; natural abiotic characteristics of nature that enable intellectual interactions. | By type of living system or environmental setting; amount by type | | | | |
| Spiritual and symbolic experience (2) | Elements of living systems: that have symbolic, sacred or religious meaning; used for entertainment or representation; natural abiotic characteristics or features of nature that enable spiritual, symbolic and other interactions. | By type of living system or environmental setting; amount by type | | | | |

*Figure 2-5: Indicator frame for cultural soil ESS (Soils4EU, (van der Meulen & Maring, 2018))*

In the report it was also highlighted that without (non-market) valuation of the ESS only a small share of the relevant effects of the land management are usually accounted in the decision-making processes, since many ESS are public goods and the use of ecosystems can be a source of externalities. They influence human well-being in less obvious and direct ways; preferences for them may not be well defined. Economic valuation helps to uncover these effects.

2020 – JRC (European Commission, 2020) **used different indicators for assessing several ESS (Biomass and timber provision, carbon sequestration, crop pollination, flood control and nature-based recreation) at country level and compiled a report with the available data sources and status of these ESS.** For instance, to assess carbon sequestration by ecosystems, data of the greenhouse gases (GHG) inventory for the Land Use, Land Use Change and Forestry sector (LULUCF), like the net emissions and removal of $CO_2$ per different land use categories, were used. For assessing the crop pollination (only by wild bees) the potential (dimensional indicators of environmental suitability to support wild insect pollinators), demand (extend of pollinator dependent crops in ha), unmet demand (extent of pollinator-dependent crops not covered by high pollination potential) and use (area where high pollination potential and demand overlap) components were assessed. In the same report in order to assess the nature-based recreation, the components which were assessed were: Potential: A) ecosystem-based potential: a dimensionless indicator of the availability of opportunities provided by nature (between 0 and 1), and B) extent of suitable areas for daily recreation (proximal high-quality areas considered as Service Providing Areas for daily recreation; in $km^2$); Demand: population (inhabitants); Use: potential visits to suitable areas for daily recreation (number of visits); and unmet demand: people living beyond 4 km from suitable areas for daily recreation.

In the **EJP SOIL D2.2** (Pavlů et al., 2021) an attempt was made to synthesize the recent and current efforts in Europe related to the establishment of soil indicators as parameters used to quantify and valuate impacts of agricultural soil management practices on soil quality. For that, information from the EU countries which participate in the EJP soil on soil quality indicators, what indicators are used to assess soil quality, for the purposes of its protection, valuation, or effective use, including information on availability and sources of these data were compiled. It was found that in each country there is a wide **range of soil information available** in various sources with **the most mentioned soil quality indicators** mentioned to be organic carbon concentration in soils and its changes in time, macronutrients (N, P, K) and micronutrients (Cu, Mn) contents in soils, soil pH, cation exchange capacity and base saturation of soils, soil texture and bulk density, and contamination with potentially toxic elements especially Cd, Co, Cr, Cu, Ni, Pb and Zn. On the other hand, water content, organic matter quality and organic carbon stocks as well as biological parameters are the less monitored soil characteristics. They also concluded that **ESS as indicator or parameter was not mentioned in any of the countries**, highlighting the need to explain and develop this topic to the policy makers and stakeholders.

In the **EJP SOIL D6.3** (Bispo et al., 2021) among others, previous existing studies, and documents on the existing national/regional soil monitoring systems in the EU countries were reviewed. It was identified that all the reviewed previous projects and initiatives mention **that soil data are available in almost all the Member States but clearly underlined the existing difficulties to compare and share data**, either due to technical issues (e.g. sampling designs and protocols, analytical methods, data format) but also to motivation (e.g. why to share the data, for what purpose) and legal requirements (e.g. are we allowed to share the data). It was concluded that **most countries are not willing to change monitoring systems but are indeed willing to modify and add new indicators in their monitoring systems and to support data harmonization**.

Recently the **European Environmental Agency** published a comprehensive report which refers primarily to indicators for soil threats at country as well as at EU level (EEA, 2022). This report presents a review of well-known soil threat indicators, their definitions and applications, and the parameters which need to be measured so that these indicators can be derived and monitored. In addition, scientific information about critical limits has been collected, beyond which soils are clearly unhealthy, not performing the quality as it is desired (i.e. soils which do not perform its functions as it is to be expected). In this report 12 soil quality indicators were selected in view of their appropriateness to assess soil degradation (unhealthy soils) related to various important soil functions or ESS for eight soil threats (Figure 2-6) and an overview of physical, chemical, and biological parameters needed to derive the soil threat indicators based on three sampling intensity

levels (Figure 2-7). The first could correspond to large-scale European wide sampling networks, the second to national monitoring networks to capture the local variability and the third serves a larger set of indicators to achieve higher accuracy for trend detections and modelling requirements (e.g. analytics for farmers). This report also tries to combine and relate soil ESS with soil threats (Figure 2-8) and also reviewed the most broadly discussed soil indicators related to these soil threats (Figure 2-9).

| Soil threat | Indicator | Thresholds | Comment |
|---|---|---|---|
| **Soil organic carbon loss** | | | |
| Cropland | Falling below optimal SOC | Light: < 1.2 [% SOC]<br>Medium: 1.2-1.9<br>Heavy: > 1.9 | SOC/Clay ratio (Johannes et al., 2017)<br>optimum SOC content as 10% of the clay content/vulnerability limit |
| **Nutrients loss** | | | |
| *Agriculture* | Exceedance of critical levels of mineral nitrogen (agricultural land) | $NH_3$ in air: 1 – 3 [mg $NH_3$ $m^{-3}$]<br>$NO_3$ in ground water: 50 [mg $NO_3$ $l^{-1}$]<br>N in surface water: 1.0 to 2.5 [mg N $l^{-1}$] | Mineral N: sum of available $NH_4$ and $NO_3$ |
| *Forest land* | N limitation based on exceedance of C/N ratio | C/N 20-25<br>leakage from forests: 1 [mg N $l^{-1}$] | Forest floor organic layer |
| *Agriculture* | Falling below of optimal phosphorus | P concentration 25-35 (optimal P fertility class) | Extractable P concentration < optimum (value range refers to Mehlich 3-ICP; also available: P-Bray P1 and Olsen P) |
| *Forest land* | P limitation based on exceedance of N/P ratio | N/P ratio > 18 (coniferous forests)<br>N/P ratio > 25 (deciduous forests) | Forest floor organic layer |
| **Acidification** | | | |
| *Agriculture* | Exceedance of critical pH levels | 1. pH < 4.5 - 4.7 (critical)<br>2. pH < 5.0 - 5.5 (avoid) | 1. Risk of Al toxicity<br>2. Limited availability of Ca, Mg, K and P |
| *Forest land* | Exceedance of critical inorganic Al levels | base cation (Bc)/aluminium ratio = 1 (0.5-2.0) | Bc = Ca+Mg+K |
| **Soil pollution** | | | |
| *All land uses* | Exceedance of screening values for critical risk from heavy metals and organic pollutants | Updated values for Cd, Cu, Pb and Zn [mg/kg] in this report<br>- by country<br>- data base developed (Cd, Cu, Pb, Zn, As, Hg, Ni, Cr)<br>- organic pollutants: | Country-specific values vary broadly and are not necessarily comparable<br>Stratification by land use and soil texture |
| **Soil erosion** | | | |
| *Agriculture* | Exceedance of actual rate of soil loss by water erosion | 2 [t ha-1 yr-1] for shallow soils (< 70 cm depth)<br>4 [t ha-1 yr-1] for deeper soils (>= 70 cm)*)<br>(soil loss tolerance) | Soil formation rate: 0.3 to 1.4 t/ha/yr (Verheijen et al. 2009)<br>Preliminary thresholds, derivation of site-adapted tolerable soil loss rates recommended<br>The current indicator description in this report only includes soil erosion by water, whereas the threshold addresses all other erosion types. |
| **Soil biodiversity loss** | | | |
| | Loss of soil biodiversity (subindicators) | to be developed:<br>(a) Exceedance of safe minimum standards of ecosystem conservation<br>(b) exceedance of operating ranges (OR) for specific soil animals and microorganisms | Requires sub-indicators by species and/or(functional) group |
| **Soil compaction** | | | |
| | Harmful subsoil compaction (subindicators) | Priority (sub) indicators:<br>Saturated hydraulic conductivity (Ks) < 10 [cm/d]<br>Air capacity (AC) < 5 [%] | Exceedance of "action values" (Zink et al. 2011)<br>Secondary subindicators with available thresholds: bulk density, internal soil strength, air permeability and oxygen diffusion |
| **Soil sealing** | | | |
| | Sealed area per land total area | National targets to achieve No Net Land Take | |

*) Loss rates lower than 2 t/ha/yr shall be mandatory on soils adjacent to water bodies, and/or soils with elevated levels of pollutants; such lower limits are needed to maintain water quality.

*Figure 2-6: Soil threat indicators investigated in the EEA report (EEA, 2022). Currently, the thresholds are available for a limited set of land uses and soil properties; in the future, all relevant land uses and sites need to be covered*

| *Monitoring levels* / *Soil threat* | **Level I** | **Level II** as with Level I, and also | **Level III** as with Level I and II, and also |
|---|---|---|---|
| **Soil organic carbon loss** | – SOC and mineral carbon<br>– Total (organic) nitrogen<br>– C:N ratio<br>– Bulk density (derived with PTF*)<br>– Texture class, stone content | – SOC fractions<br>– Bioavailability of nutrients and pollutants<br>– GHG emissions<br>– Physical parameters (measured) | Refined local SOC monitoring<br>- Management types<br>- SOC cycling at ecosystem level (input/output) |
| **Soil nutrient loss** | Agricultural soils<br>–Total N, mineral N<br>–Total P, available P: Pox/Al+Feox<br>– Available K<br>Non-agricultural soils<br>– C/N ratio, base saturation | Agricultural soils<br>–Cation exchange capacity (CEC)<br>– Base saturation<br>Non-agricultural soils<br>– Soil solution concentrations | Agricultural soils<br>- Minor nutrients<br>Non-agricultural soils<br>- as with Level II |
| **Soil acidification** | Agricultural soils<br>– pH, clay content, SOC<br>Non-agricultural soils<br>– pH, CEC, base saturation | as with soil nutrient loss | – as with soil nutrient loss |
| **Soil pollution** | – Total element concentrations (aqua regia extractable fraction of heavy metals)<br>– Natural background (at least at a subset of sampling points)<br>– Organic compounds, such as persistent organic pollutants (POPs) | – Specific soil testing, e.g., reactive or available fractions, plastics, antimicrobials<br>– Balancing (inputs-outputs, e.g., modelling) to estimate/validate accumulation) | – very specific contamination problems, e.g. radio-nuclides, military contamination, large chemical facilities<br>– site specific risk assessment tools to predict actual and future effects (of specific risks such as food quality) |
| **Soil biodiversity loss**** | – Species groups: Lumbricidae (earthworms), Collembola (springtails), Oribatida (moss mites)<br>– Species level: morphology, DNA<br>– Microbial biomass | –Species groups: Enchytraeidae (pot worms), Isopoda, (woodlice), Gamasina (predatory mites), Diplopoda, Chilopoda, Formicidae<br>–Species level: as with Level I<br>–Organic matter mineralization | – Functional diversity, e.g., feeding activity (bait-lamina)<br>– Community analysis<br>– Specific (rare/protected) species such as macrofauna (giant earthworm)<br>– Microbial diversity (DNA profile) |
| **Soil erosion** (see also Table 7-4) | – Modelling (using data on land cover/land use, geomorphological data, national soil data, rainfall) | – Mapping visible soil erosion features<br>– Details on land use (e.g., ground cover) | Monitoring (measurements) of soil erosion (sediment loads)<br>– plot scale<br>– catchment scale<br>– sediment deposition in ponds, lakes or reservoirs |
| **Soil compaction** (see also Table 8-3) | – Precompression stress (PTF)<br>– Soil rigidity ratio (PTF)<br>– Penetration resistance (PTF)<br>– Morphological features<br>– Soil organic matter (measured) | – All basic soil parameters for PTF's are measured | Tensiometer, sensors at representative subplots<br>Stress dependent measurements |
| | – Saturated hydraulic conductivity, air capacity, plant available water capacity (PTF) | | As with Level 2, but in great sampling depth, higher number of subsamples |
| | – Soil texture/coarse fragments/CaCO3 (estimated)<br>– Rooting (estimated) | | |

*) PTF Pedo-transfer functions

**) Monitoring schemes in time and space have to be developed for biodiversity and functional activities of soil organism communities, and require some adaption between Level I and II (land use, region, site conditions)

*Figure 2-7: Parameters for soil monitoring at different sampling intensity levels (EEA, 2022). The first could correspond to large-scale European wide sampling networks, the second to national monitoring networks to capture the local variability and the third serves a larger set of indicators*

*to achieve higher accuracy for trend detections and modelling requirements (e.g., analytics for farmers).*

| | | Societal needs | | | | |
|---|---|---|---|---|---|---|
| | | Biomass | Water | Climate | Biodiversity | Infrastructure |
| | Soil services | Wood & fibre production | Filtering of contaminants | Carbon storage | Habitat for plants, insects, microbes, funghi | Platform for infrastructure |
| | | Growth of crops | Water storage | | | Storage of geological material |
| Soil Threat Indicators | Soil Organic Carbon | + | + | + | + | indiff. **(i)** |
| | Soil nutrient status | + | - **(ii)** | indiff. | + | indiff. |
| | Soil acidification | - | - | indiff. **(iii)** | - | indiff. |
| | Soil pollution | - | - | - | - | indiff. **(iv)** |
| | Soil biodiversity | + | + | + | + | indiff. |
| | Soil erosion | - | - | - | - | indiff. |
| | Soil compaction | - | - | - | - | indiff. |
| | Soil sealing | - | - | - | - | + |

**(i)** Soil organic carbon / infrastructure: organic soils are instable as platform for infrastructre
**(ii)** The filtering capacity of soils prevents or buffers eutrophication and acidification
**(iii)** Soil acidification / carbon storage: fulvic acid (from acidified forest floors) enhances bleaching and nutrient loss, as well as loss of dissolved organic carbon; acidic soils slow down decomposition. From a climate point of view, soil acidification could favor carbon storage, as it leads to a lower biological activity and hence accumulation of dead biomass.
**(iv)** Land prices are lower if the soil is polluted, as remediation costs are incurred.

| LEGEND | |
|---|---|
| + | positive impact on soil service |
| - | negative impact on soil service |
| indiff. | neutral or unknown impact |

*Figure 2-8: Link between Soil Ecosystem services, key societal needs and soil threats (EEA, 2022)*

| Degradation types/soil threats | GLASOD1) | EU2) | ENVASSO indicators, modified3) | Indicators mentioned in Status of the World Soil Resources Report4) | SEEA5) and FDES6) 7) |
|---|---|---|---|---|---|
| Water erosion | X | X | - Soil loss [t/ha]<br>- Observed erosion features [type/amount per area] | Soil loss | Area affected by soil erosion** |
| Wind erosion | X | | | | |
| Overblowing | X | | - deposited soil [to/ha] | | |
| Loss of organic matter | X | X | - Topsoil organic matter (SOM) or carbon (SOC) content<br>- SOC stock [t/ha]<br>- Peat stock [t/ha] | C pool: Organic C stocks | Soil carbon* |
| Salinization | X | X | - Salinity state: total salt content [% EC]<br>- Exchangeable sodium [pH unit ESP %] | Spatial distribution of salt-affected soils | Area affected by salinization** |
| Acidification | X | (X) | - Top soil pH<br>- % exchangeable acid cations (Mn, Al, Fe) | pH<br>acid neutralization capacity | Area affected by acidification** |
| Loss of nutrients | X | (X) | - % exchangeable basic cations<br>- % trace elements (includes micronutrients) | Soil fertility: % nutrients, pH<br>Nutrient balances: N, P<br>SOM concentration | Nutrient concentrations: N, P, Ca, Mg, K, Zn, other** |
| Pollution | X | X | - Heavy metal content [mg/ha]<br>- Critical load exceedance (S, N) | Contaminated land area | |
| | | | - Progress in the management of contaminated sites | | Area/number of potentially contaminated and remediated sites** |
| Compaction and physical degradation | X | X | - Soil density<br>- Air capacity<br>- Vulnerability to soil compaction | | Area affected by compaction** |
| Waterlogging | X | | | | Area affected by waterlogging** |
| Subsidence of organic soils | X | | | | |
| Loss of soil biodiversity | | X | - Macrofauna (Earthworms)<br>- Mesofauna (Collembola)<br>- Microbial respiration | | |
| Landslides | | X | - Occurrence of landslides | | |
| Soil Sealing | | X | - Sealed area | | |
| Desertification | | X | - Vulnerability to desertification<br>- Wildfires<br>- SOC on desertified land | | Area affected by desertification** |
| Water cycle | | | - | Soil moisture | |

*Figure 2-9: Overview of broadly discussed soil quality indicators in different initiatives (Note: [1] GLASOD: GLobal Assessment of human induced SOil Degradation: 12 types of human-induced soil, [2] Soil Thematic Strategy of the European Commission (Directive (COM (2006)232), [3] ENVASSO: ENVironmental ASsessment of SOil for monitoring. 6th EU Framework Research Programme. Volume 1 identifies 290 potential indicators related to 188 key issues for 9 soil threats (Huber et al., 2008),[4] ITPS 2015, [5]EEA: System of Environmental-Economic Accounting: internationally agreed standard to produce comparable statistics and accounts (stocks and changes in stocks of environmental assets); it follows the accounting structure as the System of National Accounts (SNA). The SEEA is a guide to integrate economic, environmental and social data into a single,*

*coherent framework for holistic decision-making,* [6] *FDES: Framework for the Development of Environment Statistics (FDES 2013); it uses SEEA definitions and classifications,*[7] *by soil type, by nutrient, national, subnational (in the case of pollution: by location, subnational, by type of pollutant, by source degradation recognized).*

In the EJP SOIL SIREN project an inventory of indicator systems at national scale for assessing soil quality and ESS derived from agricultural soils as used by the EJP SOIL member states was conducted and a consistent glossary together with a comprehensive conceptual framework linking soil quality to ESS has been collated (Faber et al., 2022). A key knowledge gap which was identified by most countries is the selection and development of indicators that are translatable to targeted ESS and robust (sufficient background data, variability understood), and the quantification of the relationship between SQIs (Soil Quality Indicators) and associated ESS. They identified that at the national scale, most soil quality monitoring schemes are currently aimed to either assess soil threats or at measuring soil quality for agricultural purposes, but not for assessment of ESS in general. Moreover, the scientific development that is required to link soil data to ESS is still under development with no indicators to be delivered in the short-term. Thus, it is clear that the largest research need is to relate indicators development and quantification of soil quality - ESS relationship; the need to define and develop a complete indicator system for ESS assessment and link the soil data to ESS. They recommend standardizing and harmonize the ESS terminology to facilitate ESS assessments and promote comparability of results and for that CICES is a suitable start as long as the constrains regarding inclusion of soils will be considered in the future version. In SIREN at that moment, it is considered realistic to use a Tier approach for the implementation of an EU soil monitoring system using a minimum indicator set (Figure 2-10) for pan-European harmonization which included the indicators currently implemented by >50% of Member States as a preliminary Tier 1. As second step and Tier 2 national schemes need to be developed to cover multiple land uses and to assess soil related ESS.

| Policy Indicator | Soil Quality Indicator |
|---|---|
| Soil physical condition | Texture, Porosity,<br>Bulk density |
| Soil fertility | C concentration<br>Total N<br>P<br>K<br>pH |
| Erosion evaluation | Based on calculation |
| Salinity | Electric conductivity |
| Contamination | Heavy metal trace elements |
| Other contaminants | *Recommended to be included ** |
| Soil biodiversity | |
| Water regulation | |

*Figure 2-10: Shortlist of indicators suggested as a minimum dataset for 1st Tier of harmonized soil quality monitoring across Europe (taken from Faber et al., 2022).*

One important aspect discussed in the SIREN report and policy brief is that until now traditionally the objectives of soil assessments and soil quality monitoring were focused on assessing land degradation, as consequence of land management and use as well as the different soil threats. This approach has led to the development of the basis behind soil protection conservation and restoration but is focused on the direct objectives of the landowners and managers. They suggest that a second approach should be followed complementary, which is based on the potential of soils to provide goods and services to the broader stakeholders in society (i.e. the ESS approach, which is focused more on the positive aspects with a comprehensive scope on soil functioning and including the provision of a wide array of ESS).

Finally, with the adoption of the Directive (EU) 2025/2360 on soil monitoring and resilience (Soil Monitoring Law) in 2025, the European Union has set a legally binding framework to move towards healthy soils across the EU by 2050. The directive aims to ensure that soils can provide multiple ecosystem services at a sufficient scale to meet environmental, social and economic needs, while reducing soil pollution and degradation to levels that are no longer considered harmful to human health, the climate and the wider environment. Under this framework, Member States are required to establish and maintain a soil monitoring framework, including the regular assessment of soil health based on common EU criteria and indicators. On this basis, they will identify unhealthy soils and design appropriate regeneration and risk reduction measures at national or regional level. To describe and assess soil conditions, the Soil Monitoring Law sets out soil health criteria, soil descriptors and a set of core indicators, together with reference methods linked to the main soil degradation processes (such as erosion, loss of soil organic carbon,

compaction, contamination and loss of biodiversity). These common elements are intended to ensure comparability of soil information across the EU, while allowing Member States for some flexibility in implementation according to their specific soil, climate and land use conditions.

Nevertheless, in the majority of the earlier mentioned initiatives there is not a direct link between soil quality indicators and ESS or/and the level/scale of monitoring refers mostly to country, regional or EU level and does not cover the details and needs required for a farm level assessment (Adhikari & Hartemink, 2016). The national/regional monitoring systems and indicators can serve as a benchmark or baseline for the business models, but in most cases are not sufficient or suitable for monitoring at farm level.

## 2.3 Compilation of scientific knowledge: indicators for the quantification and measurement of soil- and agricultural management-related ecosystem services

Since there are no standard approaches for optimum sustainable soil or land management and since there are trade-offs between the different ESS, the selected and applied management depends on which ESS are demanded by society and on local soil characteristics that determine the potential for ESS.

Thus, the priorities in soil and land management will always be determined by the demand for ESS and the subjective value that decision makers or the people that they represent assign to certain services.

To enhance the different ESS delivered by the specific ecosystems and impacted by the different soil or land management options, the first step that is required it to identify these, then to properly quantify and measure them and finally to put a value to these ESS (Figure 2-11).

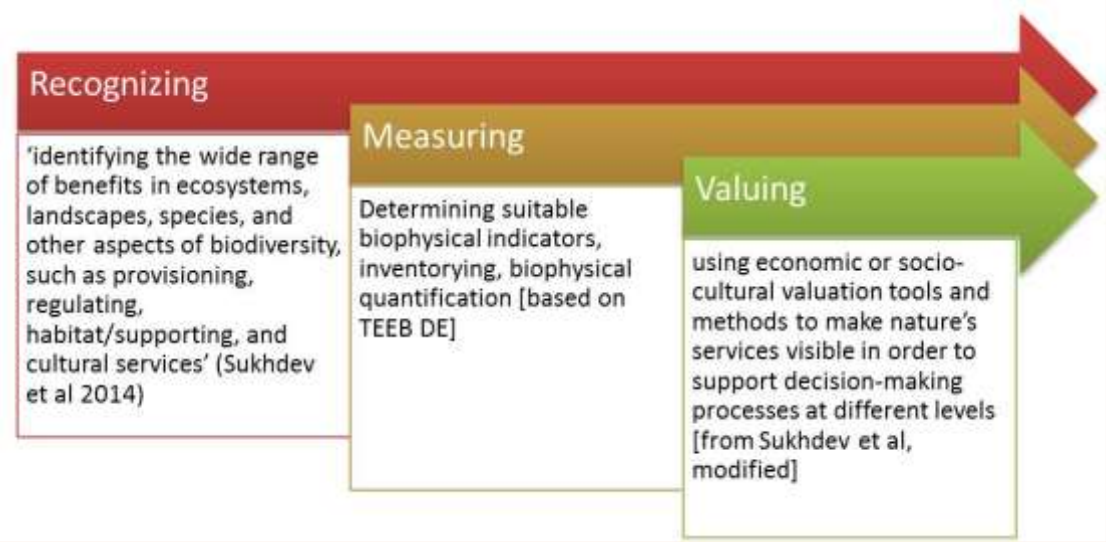



*Figure 2-11: The ESS valuation steps from recognition and identification, through (biophysical) measurement to (economic) valuation (Soils4EU D1.2 (van der Meulen & Maring, 2018))*

Enhancing the ESS delivered by the soil and management options therefore should also start with an assessment of current and future needs of humans, potential provision of ESS, and trade-offs between ESS.

Here, based on the subsets by Paul et al. (2021), we propose a list of soil- and agricultural management-related ESS that can be used by researchers, practitioners and policy maker to evaluate and rank ESS according to the local context. The selected ESS should be those that are (potentially) provided by their farming systems, represent an added value for the various stakeholders concerned and for which the farmers can be rewarded in the business models.

In the following tables (**Table 2-3**, **Table 2-4**, **Table 2-5**, **Table 2-6**, **Table 2-7**, **Table 2-8**, **Table 2-9**, Table 2-10, **Table 2-11**, **Table 2-12**) the different ESS based on the CICES v5.1 related to soil and agricultural management are presented. In the first column the ESS is described in a simple way, then the second column includes the name of the ESS class type as described in CICES v5.1, then the third and fourth columns give an example of a possible service within this class and an example of the goods or benefits provided to humans by this ESS. Then, it is visualized if the ESS is soil  or/and management  related based on the subsets of Paul et al. (2021). The management-related ecosystems are visualized with lighter color when they are relevant within specific contexts (e.g., specific geographic areas or land uses). In the column "What can be monitored", information from diverse sources as well as experts' judgement was compiled to identify the indicator frame for the different ESS

*Table 2-3: ESS related to biomass production*

| ESS related to crops and material from cultivated plants (Biomass production) | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | CICES Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |
| Any crops and fruits grown by humans for food and feed | Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes | 1.1.1.1 | Standing wheat crop before harvest | Harvested crop; Grain in farmer's store |  | Crop yield amount, surface area |
| Material from plants, fungi, algae or bacterial that we can use as raw materials for non-nutritional purposes | Fibers and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials) | 1.1.1.2 | Harvestable surplus of annual tree growth | Processed timber (Volume of harvested wood) |  | Material amount/volume, surface area |
| Plant materials used as a source of energy | Cultivated plants (including fungi, algae) grown as a source of energy | 1.1.1.3 | Standing crop of Miscanthus at time of harvest | Energy production |  | Crop yield amount/energy equivalent, surface area |

*Table 2-4: ESS related to water used for drinking or as material*

| ESS related to water used for drinking or as material | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |
| Drinking water from sources at the ground surface | Surface water for drinking | 4.2.1.1 | Volume and characteristics of water from a natural spring | Potable water in public supply system |  | Water amount and characteristics, water abstraction |

| | | | | | | |
|---|---|---|---|---|---|---|
| Surface water that we can use for things other than drinking | Surface water used as a material (non-drinking purposes) | 4.2.1.2 | Temperature and volume of water that can be used for cooling, or irrigation | Reduced energy costs |  | Water amount and characteristics, water abstraction |
| Drinking water from the below ground | Ground (and subsurface) water for drinking | 4.2.2.1 | Aquifer volume and characteristics | Potable water in public supply system; mineral water |  | Aquifer water amount and characteristics, water abstraction |
| Sub-surface water that we can use for things other than drinking | Ground water (and subsurface) used as a material (non-drinking purposes) | 4.2.2.2 | Characteristics and volume of water that can be used for washing purposes | Reduced material costs |  | Water amount and characteristics, water abstraction |

*Table 2-5: ESS related to water purification and waste treatment*

| ESS related to water purification and waste treatment | | | | | | |
|---|---|---|---|---|---|---|
| **Simple description** | **Class** | **CICES Code** | **Example Service** | **Example Goods and Benefits** | **Relevance** | **What can be monitored** |
| Decomposing wastes | Bioremediation by micro-organisms, algae, plants, and animals | 2.1.1.1 | Transformation of an (in) organic substance by a species of plant, animal, bacteria, fungi or algae that mitigates its harmful effects and reduces the costs of disposal by other means. e.g., Bioremediation of industrial waste by disposal on agricultural land | Sustainable disposal of wastes, |  | Concentration of pollutants in soil/water, heavy metals trace elements, |

| | | | | | | |
|---|---|---|---|---|---|---|
| Filtering wastes | Filtration/sequestration /storage/ accumulation by micro-organisms, algae, plants, and animals | 2.1.1.2 | Dust filtration by urban trees, Soil provides a habitat to vegetation that influences air quality. | Reduction in respiratory disease |  | Concentration of pollutants in soil or water, air pollutants removed by vegetation in leaves stems, heavy metals trace elements, |
| Natural processing of wastes | Mediation by other chemical or physical means (e.g., via filtration, sequestration, storage, or accumulation) | 5.1.1.3 | Dissolved soil particles in runoff | Biogeochemical effects of reduced dissolved soil particles |  | Concentration of pollutants in soil or water, air pollutants removed by vegetation in leaves stems, heavy metals |
| Controlling the chemical quality of freshwater | Regulation of the chemical condition of freshwater by living processes | 2.2.5.1 | Removal of nutrients in runoff (e.g. using buffer strips along water courses) | Reduced damage costs nutrient runoff from agroecosystems |  | Water chemical quality, Concentration of pollutants, heavy metal trace elements |
| Controlling the chemical quality of salt water | Regulation of the chemical condition of salt waters by living processes | 5.1.1.3 | Dissolved soil particles in runoff | Biogeochemical effects of reduced dissolved soil particles |  | Concentration of pollutants in soil or water, air pollutants removed by vegetation in leaves stems, heavy metals |

*Table 2-6: ESS related to erosion regulation and prevention and flood risk*

| ESS related to erosion regulation and prevention & flood risk | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |

| | | | | | | |
|---|---|---|---|---|---|---|
| Controlling or preventing soil loss | Control of erosion rates | 2.2.1.1 | The capacity of vegetation to prevent or reduce the incidence of soil erosion | Reduction of damage (and associated costs) of sediment input to water courses |  | Risk reduction, Soil mass, sediment losses, land management options, area affected, observed erosion features |
| Stopping landslides and avalanches harming people | Buffering and attenuation of mass movement | 2.2.1.2 | The capacity of forest cover to prevent or mitigate the extent and force of snow avalanche | Reduction in cost to human lives and physical damage to infrastructure |  | Risk reduction, Area protected, occurrence of landslides |
| Regulating the flow of water in our environment | Hydrological cycle and water flow regulation (Including flood control, and coastal protection) | 2.2.1.3 | The capacity of vegetation to retain water and release it slowly, | Mitigation of damage because of reduced in magnitude and frequency of flood/storm events |  | Water retention capacity (volume / depth), soil moisture |
| Physical barriers to flows | Liquid flows | 5.2.1.2 | Soil erosion constructions to lower the risk of runoff water going to roads or small rivers | Reduction in damage costs |  | Risk reduction, Area protected |

*Table 2-7: ESS related to humans' protection from nuisances, extreme events and weather conditions*

| ESS related to humans' protection from nuisances, extreme events and weather conditions | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |
| Regulating the physical quality of air for people | Regulation of temperature and humidity, including ventilation and transpiration | 2.2.6.2 | Soil provides a habitat to vegetation that provides shading and cooling through evapotranspiration. Perceived thermal comfort may also be higher in a green environment. | Increased thermal comfort |  | Amount, concentration of climatic parameter |

| | | | | | | |
|---|---|---|---|---|---|---|
| Protecting people from winds | Wind protection | 2.2.1.4 | Wind breaks | Reduction in scale or frequency of damage to crops |  | Risk reduction, Area protected |
| Protecting people from fire | Fire protection | 2.2.1.5 | The capacity of ecosystems to reduce the frequency, spread or magnitudes of fires. (e.g., wetland area between forests, or fire belt in woodland containing species of low combustibility) | Reduction in fire damage costs |  | Risk reduction, Area protected |
| Screening unsightly things | Visual screening | 2.1.2.3 | Shelter belts around industrial structures | Visual amenity |  | |
| *Reducing smells | Smell reduction | 2.1.2.1 | Shelter belts that filter particulates that carry odors | Reduction in nuisance effect of smells from animal lots |  | |
| *Reducing noise | Noise attenuation | 2.1.2.2 | Shelter belts along motorways, Adsorption of noise by open soil, and soil also provides a substrate for vegetation that can reduce noise. | Low noise environment |  | Leaf Area Index + distance to roads |

*These ESS are not included in Paul et al. (2021) classification

*Table 2-8: ESS related to GHG regulation and soil quality*

| ESS related to GHG regulation and soil quality | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |

| | | | | | | |
|---|---|---|---|---|---|---|
| Regulating our global climate | Regulation of chemical composition of atmosphere and oceans | 2.2.6.1 | Sequestration of carbon in peatlands | Climate regulation resulting in avoided damage costs; Rewetting peatlands to maintain the C; |  | Carbon sequestration and regulation of GHG, peat stock |
| Ensuring the organic matter is maintained | Decomposition and fixing processes and their effect on soil quality | 2.2.4.2 | Decomposition of plant residue; N-fixation by legumes | legumes used to increase/maintain C and N-levels in soil; reduction of soil disturbances |  | Soil C, N, BD, texture Management type, SOC balance in the ecosystem, |
| Ensuring soils form and develop | Weathering processes and their effect on soil quality | 2.2.4.1 | Inorganic nutrient release in cultivated fields | Maintenance of soil quality and hence capability of soil for human use. |  | |

*Table 2-9: ESS related to pollination & biodiversity maintenance and control*

| ESS related to pollination & biodiversity maintenance and control | | | | | | |
|---|---|---|---|---|---|---|
| **Simple description** | **Class** | **CICES Code** | **Example Service** | **Example Goods and Benefits** | **Relevance** | **What can be monitored** |
| Pollinating our fruit trees and other plants | Pollination (or 'gamete' dispersal in a marine context) | 2.2.2.1 | Providing a habitat for native pollinators | Contribution to yield of fruit crops |  | Amount of extra yield attributed to pollination, types of pollinators |
| Controlling disease | Disease control | 2.2.3.2 | Increased below ground biodiversity that regulates soil borne diseases, functional agrobiodiversity practices such as mixed rotation for regulating disease | Reduction in disease damage due to harvested fruit or vegetables; Reduced use of fungicides |  | Risk reduction, Area protected |

| | | | | | | |
|---|---|---|---|---|---|---|
| Providing habitats for wild plants and animals that can be useful to us | Maintaining nursery populations and habitats (Including gene pool protection) | 2.2.2.3 | Important nursery habitats include estuaries, seagrass, kelp forest, wetlands, soft sediment, hard bottom, shell bottom and water column habitats | Sustainable populations of useful or iconic species that contribute to a service in another ecosystem. |  | Species and varieties and functional group |
| Controlling pests and invasive species | Pest control (including invasive species) | 2.2.3.1 | Providing a habitat for native pest control agents | Reduction in pest damage to cultivated crop |  | Risk reduction, Area protected |
| Spreading the seeds of wild plants | Seed dispersal | 2.2.2.2 | Acorn dispersal by Eurasian Jays | Tree regeneration in parkland |  | |
| Seed collection | Seeds, spores and other plant materials collected for maintaining or establishing a population | 1.2.1.1 | Seeds or spores that we can harvest | Wild plant seed for commercial sale |  | |
| Plants fungi or algae that we can use for breeding | Higher and lower plants (whole organisms) used to breed new strains or varieties | 1.2.1.2 | Population of plant algae or fungi species used to in breeding programs | Plant, algae or fungi species with novel characteristics that increase yields or reduce costs by resisting diseases or pests |  | |

*Table 2-10: ESS related to recreation, culture, education etc.*

| ESS related to recreation, culture, education etc. | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |
| Using the environment for sport and recreation; using nature to help stay fit | Characteristics of living systems that that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions | 3.1.1.1 | Ecological qualities of woodland that make it attractive to hiker; private gardens, Opportunities for diving, swimming | Recreation, fitness; de-stressing or mental health; nature-based recreation |  | Number of visitors |
| Watching plants and animals where they live; using nature to destress | Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through passive or observational interactions | 3.1.1.2 | Mix of species in a woodland of interest to birdwatchers | Recreation, fitness; de-stressing or mental health; eco-tourism |  | Number of visitors |
| The things in nature that help people identify with the history or culture of where they live or come from | Characteristics of living systems that are resonant in terms of culture or heritage | 3.1.2.3 | Sherwood Forest | Tourism, local identify |  | Number of visitors |
| The beauty of nature | Characteristics of living systems that enable aesthetic experiences | 3.1.2.4 | Area of Outstanding Natural Beauty; panorama site | Artistic inspiration |  | Number of visitors |
| Researching nature | Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge | 3.1.2.1 | Site of special scientific interest, Natura 2000 site | Knowledge about the environment and nature |  | Number of visitors |

| | | | | | | |
|---|---|---|---|---|---|---|
| Studying nature | Characteristics of living systems that enable education and training | 3.1.2.2 | Site used for voluntary conservation activities, research (e.g. historic climate change) | Skills or knowledge about environmental management |  | |
| Using nature to as a national or local emblem | Elements of living systems that have symbolic meaning | 3.2.1.1 | Bald Eagle, battlefields, | Social cohesion, cultural icon |  | |
| The things in nature that have spiritual importance for people | Elements of living systems that have sacred or religious meaning | 3.2.1.2 | ceremonial sites, and cemeteries. | Mental well-being |  | |
| The things in nature used to make films or to write books | Elements of living systems used for entertainment or representation | 3.2.1.3 | Archive records or collections | Nature films |  | |
| The things in nature that we think should be conserved | Characteristics or features of living systems that have an existence value | 3.2.2.1 | Areas designated as wilderness | Mental/Moral well-being |  | |
| The things in nature that we want future generations to enjoy or use | Characteristics or features of living systems that have an option or bequest value | 3.2.2.2 | Endangered species or habitat | Moral well-being |  | |

*Table 2-11: ESS related to crops and material from wild plants*

| ESS related to crops and material from wild plants | | | | | | |
|---|---|---|---|---|---|---|
| **Simple description** | **Class** | **CICES Code** | **Example Service** | **Example Goods and Benefits** | **Relevance** | **What can be monitored** |
| Food from wild plants | Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition | 1.1.5.1 | Harvestable volume of wild berries or wild mushrooms, | Berries as food or to produce jam |  | Crop yield amount, surface area |

| | | | | | | |
|---|---|---|---|---|---|---|
| Materials from wild plants | Fibers and other materials from wild plants for direct use or processing (excluding genetic materials) | 1.1.5.2 | Harvestable volume of reeds; Macroalgae used for thickening agents, agar, and superconductor electrodes | Roofing material |  | Material amount/volume, surface area |
| Materials from wild plants, fungi and algae used for energy | Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy | 1.1.5.3 | Volume of harvested wood | Fuel wood |  | Crop yield amount/energy equivalent, surface area |

*Table 2-12: ESS related to soil minerals used for food or other purposes (raw materials)*

| ESS related to soil minerals used for food or other purposes (raw materials) | | | | | | |
|---|---|---|---|---|---|---|
| Simple description | Class | CICES Code | Example Service | Example Goods and Benefits | Relevance | What can be monitored |
| Minerals in our food | Mineral substances used for nutritional purposes | 4.3.1.1 | Salt | Dietary value |  | Raw material abstraction amount |
| Natural inorganic materials from nature we can use | Mineral substances used for material purposes | 4.3.1.2 | Pigments, clay or sand | Decoration |  | Raw material abstraction amount |

# 3. Business Models and soil health programs

This chapter provides a detailed analysis of existing business models and programs for creating incentives and for generating revenues from healthy soils. The aim is to compile a list of promising business models and soil health programs that can be used as a catalogue by the testing grounds, communities of practices and the broader stakeholder community in the subsequent tasks and work packages. Extra attention is paid to the monitoring systems used by these business models and soil health programs to assess and evaluate soil health and soil-related ESS.

## 3.1 Exploration of existing business models and related programs in which soil health and ecosystem services are main drivers

The economic valuation of soil health and soil-related ESS is a relatively recent concept that has been largely driven by the wave of modern environmentalism in the second half of the 20$^{th}$ century (Gómez-Baggethun et al., 2010). It has only been in the last four decades that incentive schemes, which tried to internalize the positive externalities that come with healthy soils and sustainable land management, started to pop up (Gómez-Baggethun et al., 2010; Salzman et al., 2018). Most of these earliest schemes, like the Conservation Reserve Program in the United States (initiated in 1985 - Goodwin & Smith, 2003), the Countryside Stewardship Scheme (CSS) in the UK (initiated in 1991 - Dobbs & Pretty, 2008) and the Costa Rican national payment scheme for the forestry sector (initiated in 1997 - Pagiola, 2008), were established and funded by national governments (Börner et al., 2017). These schemes gave the government alternative tools, besides regulation, to ensure the provision of ESS that benefited the general public (Winkel et al., 2022; Wunder, 2015). It is only in more recent years that the first privately funded business models were established. Payment has been the predominant economic incentive for both privately and publicly funded schemes. Standardly the term Payment for Ecosystem Services (PES) is used to describe these voluntary and conditional transactions over well-defined ESS between at least one supplier (e.g. farmers, landowners), which has agreed to take certain actions to manage their land or watershed to provide an ESS, and one user (e.g. individuals, communities, businesses, governments, NGOs), which benefits from the ESS (Smith et al., 2013; Wunder, 2015). The basic idea is that whoever provides a service should be paid for doing so. PES therefore provides an opportunity to put a price on previously un-priced ESS, like climate regulation or the provision of habitat for wildlife, which brings them into the wider economy and provides financial returns on top of the agricultural ones (Smith et al., 2013). However, payment is not the only incentive, or reward, utilized for this purpose. Alternative incentive mechanisms include: certification or labelling (e.g. Farm for Good in Belgium), financial advice to make the farm more profitable (e.g. Soil Association Exchange in

the UK), supply of cheap or free inputs (e.g. Bloemenstroken voor meer biodiversiteit by Tiense Suiker in Belgium), offering free use of land or at reduced land lease (e.g. Beernem Carbon farming in Belgium, where communal land is made available to farmers who are willing to implement farming practices that promote carbon sequestration), and trading system, also referred to as Markets for Ecosystem services (MES) (e.g. biodiversity offsetting or emission trading) (Bayon, 2004; Smith et al., 2013). Lowering interest rates by banks was mentioned by Baayen et al. (2022) as an alternative incentive mechanism. However, we could not find any examples of its use in existing business models or soil health programs. It is possible that this incentive mechanism is currently only used in programs that are implemented in regions of the world that fall outside the scope of our exploration (i.e. Europe, or regions with a similar climate).

In Table 3-1 we present the results of our exploration of existing business models and related programs in which soil health and soil-related ESS are the main drivers. Since monitoring systems to assess and evaluate soil health and soil-related ESS are highly relevant for (the further tasks and work packages of) SoilValues, we decided to broaden the scope of our search from business models to also include programs and tools focusing on the assessment of soil-related ESS. To keep a clear distinction between the different types of programs, we first divided them between business models, which were here defined as (at least partially) privately funded market-based schemes to create economic incentives for the provision of ecosystem services, and non-business models, which included publicly funded incentive schemes, like Environmental Stewardship in the UK (also includes programs that provide access to communal lands – e.g. Beernem Carbon Farming in Belgium), agroecological assessment tools, like OASIS, environmental mapping and planning tools, like Ecoplan for Flanders, and knowledge exchange and research projects, like Carbon action in Finland. Within the business models a distinction was made between the different reimbursement or incentive mechanisms: direct payment, labeling or certification and financial advice. At the end of our extensive search in related scientific literature and online, we found a total of 92 programs with soil health and soil-related ESS as main drivers, of which 48 fitted our definition of business model. The latter group included 43 schemes that used payment as incentive or reward, four that provided the farmer or landowner with a specific label or certificate, and one that gave financial advice to make the farm more profitable, based on the provision of ESS. Of the other programs, 19 counted on public funding, 17 were focused on the assessment of soil health and ESS (often related to sustainable or agroecological agriculture), four were environmental mapping or planning tools, three were knowledge exchange or research projects and one provided farmers with free inputs (in this case seeds for flower strips in sugar beet fields).

Of the programs listed in Table 3-1 fourteen were not restricted by geographic location, but only four of these could be defined as business models (e.g. the PES scheme of Earthworm or the labelling service of Ecological Outcome Verification). Our search was primarily focused on Europe but not limited to it. Programs that focused on regions with climates that are dissimilar to Europe, like tropical and desert, were excluded from the inventory. Within Europe we found most programs for the UK (14), the Netherlands (12), Germany (10), Belgium (10) and France (9). Outside Europe most of the listed programs were focused on the USA (10). The relatively low numbers of programs for Southern and Eastern Europe and Scandinavia might have been caused by language constraints during our search.

For most programs (43) the agricultural land-use was not specified, which often implied all land-uses. The remaining programs explicitly mentioned land-use, with 39 focusing on arable land, 29 on grassland, four on horticulture and two on agroforestry.

The programs listed in Table 3-1 could be further divided based on their stated topic of focus. Here we made broad distinctions between programs that looked at sustainable farming (41 – e.g. agroecology, regenerative farming, biodiversity, soil health), carbon farming or sequestration (31 – broadened to include reduction in greenhouse gas emissions), broad hydrological functions (11 – e.g. drinking water quality, flood control) and ESS in general (10). Limited to the business models, the largest group of programs became the carbon farming schemes (22), followed by the sustainable farming schemes (14), the hydrological functions schemes (10) and only two that focused on ESS in general. This order in the number of business models is consistent with the order given by Gómez-Baggethun et al. (2010) for PES schemes. The proportionally large number of business models that focus on carbon farming or sequestration is probably linked to the broad concern for the reduction of carbon emissions. The resulting set of new goals and regulations (see e.g. the Paris Agreement, the European Green Deal and the 2030 Agenda for Sustainable Development) have pushed companies and governmental institutions to look for means to offset their own emissions. It seems that carbon sequestration in agricultural land is considered a viable strategy for doing this. A further explanation for the popularity of carbon farming programs could be the relatively simple methods of quantifying carbon sequestration (both via field measurements and modelling).

Table 3-1 also lists the ESS mentioned by the programs. This includes both the primary ESS of focus, like carbon sequestration in most carbon farming schemes, and the co-benefits. Shortened descriptions of the ESS are given to better utilize the limited spacing in the tables. This way of describing the ESS, like biodiversity to mean the provision of habitat for wildlife, was itself also

utilized in most of the discovered programs. Unsurprisingly, carbon sequestration is mentioned most in our inventory (75), closely followed by biodiversity (62) and water-related ESS (60). Erosion control (30), flood control (16), pollination (12) and climate resilience (12) were mentioned less often.

*Table 3-1: Inventory of business models and related programs in which soil health and ecosystem services are the main drivers.*

| Program | Source | Stated focus | Countries (Region) | Land-use | Business model | Type of reimbursement | Mentioned soil-related ESS |
|---|---|---|---|---|---|---|---|
| Soil Association Exchange | https://www.soilassociationexchange.com/ | Regenerative farming | UK | All | Yes | Financial advice | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) |
| Farm for Good | https://www.farmforgood.org/ | Agroecology | Belgium (Wallonia) | All | Yes | Label | No information given |
| FarmFacts | https://www.nextfarming.de/landwirt/ | Environmental services | Germany (Bavaria & Baden-Württemberg) | Arable | Yes | Label | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) |
| Ecological Outcome Verification | https://savory.global/eov/ | Regenerative farming | Worldwide | Grassland | Yes | Label | -Biodiversity<br>-Carbon sequestration<br>-Water (storage) |
| On the way to PlanetProof | https://www.planetproof.eu | Sustainability | the Netherlands | -Arable<br>-Horticulture<br>-Grassland | Yes | Label | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (quality) |
| Pour une Agriculture du Vivant | https://agriculturedu vivant.org/ | Agroecology | France | -Arable<br>-Fruit crops<br>-Vineyards<br>-Hops | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & quality) |
| LandvanWaard | https://landvanwaarde.nl/ | Biodiversity | the Netherlands (Overijssel) | -Arable<br>-Grassland | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Pollination |
| Claire | https://claire-co2.com/ | Carbon compensation | Belgium | All | Yes | Payment | Carbon sequestration |
| AgreenaCarbon | https://agreena.com/da/carbon/landmaend/ | Carbon farming | Denmark | Arable | Yes | Payment | -Biodiversity<br>-Carbon sequestration |
| CarboAgrar | https://www.carboagrar.de/ | Carbon farming | -Germany<br>-Denmark<br>-Poland | Arable | Yes | Payment | -Carbon sequestration<br>-Erosion control<br>-Water (storage) |
| Carbon Farmers | www.carbonfarming.nl | Carbon farming | the Netherlands | -Grassland | Yes | Payment | -Biodiversity<br>-Carbon sequestration |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | -Elephant grass<br>-Bamboo<br>-Paulownia trees | | | -Climate resilience<br>-Erosion control<br>-Flood control<br>-Water (storage & quality) |
| Carboneg | https://carboneg.eu/cs | Carbon farming | -Czech Republic<br>-Hungary<br>-Slovakia<br>-Romania<br>-South Africa<br>-Kyrgyzstan | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration |
| CO2-land | https://co2-land.org/ | Carbon farming | Germany | All | Yes | Payment | -Carbon sequestration<br>-Climate resilience<br>-Biodiversity<br>-Water (storage & quality)<br>-Erosion control<br>-Flood control |
| Dutch Carbon Credits | https://www.dutchcarboncredits.nl/ | Carbon farming | the Netherlands | Grassland | Yes | Payment | Carbon sequestration |
| Indigo | https://www.indigoag.eu/for-growers/carbon-farming | Carbon farming | -USA<br>-Germany<br>-Hungary<br>-Ukraine<br>-Turkey | Arable | Yes | Payment | -Carbon sequestration |
| Klim.eco | https://www.klim.eco/ | Carbon farming | Germany | Arable | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control |
| Nori | https://nori.com/ | Carbon farming | USA | Arable | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Flood control<br>-Water (storage & quality) |
| Positerra | https://positerra.org/ | Carbon farming | Germany | -Arable<br>-Horticulture | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Rabo Carbon bank | https://www.rabobank.com/about-us/carbon-bank | Carbon farming | -USA<br>-the Netherlands | Arable | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & quality) |
| Svensk Kolinlagring (Swedish carbon storage) | https://kolinlagring.se/ | Carbon farming | Sweden | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Water (storage) |
| Wisber EU | https://wisber.eu/himmelserde/zertifikate%20kaufen.html https://himmelserde.jimdofree.com/ | Carbon farming | Germany (Bavaria - around Munich) | All | Yes | Payment | -Carbon sequestration<br>-Water (storage) |
| CAR Soils | https://www.climateactionreserve.org/how/protocols/ncs/soil-enrichment/ | Carbon offset | USA | All | Yes | Payment | Carbon sequestration |
| BCarbon | https://bcarbon.org/ | Carbon sequestration | USA | All | Yes | Payment | Carbon sequestration |
| CarboCert | https://www.carbocert.de/ | Carbon sequestration | -Germany<br>-Switzerland | -Arable<br>-Grassland<br>-Agroforestry<br>-Forestry (conversion) | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Water (quality)<br>-Erosion control |
| Humus+ Modell Ökoregion Kaindorf | https://www.humusplus.at/ | Carbon sequestration | -Austria<br>-Slovenia | -Arable<br>-Grassland | Yes | Payment | -Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) |
| Soil Capital | https://soilcapital.com/ | Carbon sequestration | -Belgium<br>-France<br>-UK | Arable | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience |
| Windpark Krammer | https://www.zeeuwind.nl/nieuws/koolstof-binden-de-bodem-rondom-windpark-krammer | Carbon sequestration | the Netherlands (Zeeland) | Arable | Yes | Payment | -Carbon sequestration<br>-Water (storage) |
| Zukunft Erde | https://www.onfarming.at/inhalt/sortiment-ratgeber/ratgeber/landwirte/ackerbau/dungung/mit-zukunft-erde-humus-aufbauen | Carbon sequestration | Austria | -Arable<br>-Grassland | Yes | Payment | Carbon sequestration |
| Cool Crowd project | www.COOLCROWD.no | Climate friendly agriculture | Norway | Grassland | Yes | Payment | Carbon sequestration |

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|---|---|---|---|---|---|---|---|
| Agrivair (Vittel) | https://www.vittel.fr/agrivair-protection-nappe-phreatique-vittel-eau-minerale<br>https://www.valvert.be/nl-be/bescherming-van-de-bron-van-valvert | Drinking water protection | France (Vittel)<br>Belgium (Etalle) | All | Yes | Payment | -Biodiversity<br>-Water (supply & quality) |
| APIEME | https://www.evian.com/en_int/our-sustainability-actions/source-protection/ | Drinking water protection | France (Évian-les-Bains area) | Grassland | Yes | Payment | -Biodiversity<br>-Water (supply & quality) |
| DWPS | https://www.scottishwater.co.uk/About-Us/Energy-and-Sustainability/Sustainable-Land-Management/Drinking-Water-Protection-Scheme | Drinking water protection | UK (Scotland) | -Arable<br>-Grassland | Yes | Payment | Water (quality) |
| SCaMP | https://www.unitedutilities.com/corporate/responsibility/stakeholders/catchment-systems-thinking/catchment-management/ | Drinking water protection | UK (England) | All | Yes | Payment | -Biodiversity<br>-Water (quality) |
| Wessex Water Catchment Management | https://corporate.wessexwater.co.uk/our-purpose/rivers-and-coastal-waters/catchment-management | Drinking water protection | UK (Southwest England) | All | Yes | Payment | -Biodiversity<br>-Water (quality) |
| Naturellement Popcorn | https://www.cesbio.cnrs.fr/agricarboneo/naturellement-popcorn/ | Ecological transition for maize production | France | Maize | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (quality) |
| OleoZE | https://www.oleomarket.fr/oleoze | Ecological transition for rapeseed and sunflower production | France | -Rapeseed<br>-Sunflower | Yes | Payment | -Carbon sequestration |
| BEF Water Certificates | https://www.b-e-f.org/programs/water-restoration-certificates/ | Ecological use of water supplies | USA | All | Yes | Payment | -Biodiversity<br>-Water (supply & quality) |
| Slowing the flow at Pickering | https://www.northyorkmoors.org.uk/looking-after/our-projects-and-partnerships/previous-projects/slowing-the-flow | Flood control | UK (North Yorkshire) | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control |
| Upstream Thinking | https://wrt.org.uk/project/ust2/ | Improving water quality | UK (Southwest England) | -Arable<br>-Grassland | Yes | Payment | -Biodiversity<br>-Carbon sequestration |

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|---|---|---|---|---|---|---|---|
| | | | | | | | -Erosion control<br>-Flood control<br>-Water (quality) |
| Pumlumon Project | https://www.montwt.co.uk/projects/pumlumon-project | Payment for ecosystem services | UK (Wales) | -Grassland<br>-Forestry | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control<br>-Water (storage & quality) |
| Verified carbon standard | https://verra.org/programs/verified-carbon-standard/ | Reduction and removal of greenhouse gas emissions | Worldwide | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Additional (claimed but not specified) |
| Climate farmers | https://www.climatefarmers.org/ | Regenerative farming | -Spain<br>-Portugal<br>-Italy<br>-Germany | -Arable<br>-Grassland<br>-Agroforestry | Yes | Payment | -Carbon sequestration<br>-Climate resilience<br>-Water (storage) |
| Danone | www.danone.pl/rolnictwo-regeneratywne/ | Regenerative farming | Poland | Grassland | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage) |
| Nestlé | https://www.nestle.com/sustainability/nature-environment/regenerative-agriculture | Regenerative farming | Worldwide | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Water (storage & quality) |
| Soil Heroes | https://soilheroes.com/farmers/ | Regenerative farming - Soil health | Europe | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & regulation) |
| Earthworm - Living Soils Project | https://www.solsvivants.org/en/<br>https://www.earthworm.org/ | Sustainability - Nature regeneration | Earthworm: Worldwide<br>Living Soils Initiative: France | All | Yes | Payment | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & regulation) |
| NutrientNet | https://nutrientnet.org/about.cfm#what | Water quality | USA | All | Yes | Payment | Water (quality) |
| Westcountry angling Passport | https://wrt.org.uk/project/westcountry-angling-passport/ | Water quality streams | UK (Southwest England) | All | Yes | Payment | -Biodiversity<br>-Water (quality) |

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|---|---|---|---|---|---|---|---|
| GTAE | file:///C:/Users/advanderhasselt/Downloads/memento_gret_uk_web.pdf | Agroecology | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) |
| OASIS | https://www.agroecology-europe.org/oasis-brochure/ | Agroecology | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control<br>-Pollination<br>-Water (storage & quality) |
| TAPE | https://www.fao.org/agroecology/tools-tape/en/ | Agroecology | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) |
| GAIA biodiversity yardstick | https://gaia-biodiversity-yardstick.eu/ | Biodiversity | Northwest Europe | -Arable<br>-Grassland | No | Assessment | Biodiversity |
| Agrinewal | https://agrinewal.com/ | Carbon balance | Ireland | Grassland | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) |
| World-Climate Farm Tool | https://www.carbon-standards.com/en/standards-and-services/service-499~farm-tool.html | Carbon footprint | Worldwide | All | No | Assessment | Carbon sequestration |
| EFA Calculator | http://sitem.herts.ac.uk/aeru/efa/ | Semi-natural habitats (or ecological focus areas) providing ecological services | Europe | All | No | Assessment | -Carbon sequestration<br>-Erosion control<br>-Flood protection<br>-Global climate regulation<br>-Pest control<br>-Water (supply, regulation & quality) |
| Global farm metric | https://www.globalfarmmetric.org/ | Sustainability | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & quality) |
| IDEA | https://outils-idea.inrae.fr/ | Sustainability | France | All | No | Assessment | -Pollination<br>-Water (storage & quality) |

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|---|---|---|---|---|---|---|---|
| LEAF Sustainable Farming Review | https://leaf.eco/farming/review#:~:text=The%20LEAF%20Sustainable%20Farming%20Review,improvement%20across%20the%20whole%20farm. | Sustainability | UK | All | No | Assessment | -Carbon sequestration<br>-Erosion control<br>-Global climate regulation<br>-Water (supply, regulation) |
| Origin Green | https://www.origingreen.ie/ | Sustainability | Ireland | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) |
| RISE | https://www.bfh.ch/en/research/all-our-consulting-services/rise/ | Sustainability | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) |
| SAFA | https://www.fao.org/nr/sustainability/sustainability-assessments-safa/en/ | Sustainability | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Flood control<br>-Landslide control<br>-Pollination<br>-Water (storage & quality) |
| SAFE | https://www.belspo.be/belspo/organisation/publ/pub_ostc/CPgen/rappCP28leaflet_en.pdf | Sustainability | Belgium | -Arable<br>-Grassland | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) |
| SMART | https://www.fibl.org/en/themes/smart-en | Sustainability | Worldwide | All | No | Assessment | No information given |
| Genesis | https://en.genesis.live/ | Sustainability of agricultural supplies, environmental impact & soil health | Worldwide | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) |
| Openbodemindex | https://openbodemindex.nl/ | Soil health | the Netherlands | All | No | Assessment | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (quality)<br>-Water (supply, infiltration, retention) |

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| Ecoplan | https://www.uantwerpen.be/nl/onderzoeksgroep/ecoplan/ | Ecosystem services | Belgium (Flanders) | All | No | Environmental planning | -Carbon sequestration<br>-Erosion control<br>-N storage<br>-P storage<br>-Water (supply, infiltration, retention) |
| Ecosystems Flanders | https://www.vlaanderen.be/inbo/datasets/ecosysteemdiensten-vlaanderen/ | Ecosystem services | Belgium (Flanders) | All | No | Environmental planning | -Erosion control<br>-Flood control<br>-Water (supply, quality regulation) |
| MAES | https://publications.jrc.ec.europa.eu/repository/handle/JRC120383 | Ecosystem services | Europe | All | No | Environmental planning | -Carbon sequestration<br>-Flood control |
| LIFE Viva Grass | https://vivagrass.eu/ | Maintenance of biodiversity and ecosystem services provided by grasslands | -Estonia<br>-Latvia<br>-Lithuania | Grassland | No | Environmental planning | -Bioremediation by micro-organisms, plants and animals<br>-Chemical condition of freshwaters<br>-Erosion control<br>-Filtration, storage & accumulation of nutrients<br>-Global climate regulation<br>-Maintaining habitats<br>-Pollination and seed dispersal<br>-Provision of cultivated crops<br>-Provision of reared animals and their outputs<br>-Provision of fodder<br>-Provision of Biomass-based energy sources<br>-Provision of herbs for medicine |

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| | | | | | | | -Weathering processes/soil fertility |
| Bloemenstroken voor meer biodiversiteit (Tiense Suiker) | https://www.tiensesuiker.com/bloemstroken/ | Biodiversity | Belgium | Sugar beet | No | Free seed of flower mix | -Biodiversity<br>-Carbon sequestration<br>-Pollination<br>-Water (quality) |
| Carbon action (Finland) | https://carbonaction.org/en/front-page/ | Regenerative & carbon farming | Finland | All | No | Knowledge exchange | -Biodiversity<br>-Carbon sequestration |
| Arla's Regenerative Farming Pilot Network | https://www.arla.com/4a6ee6/globalassets/sustainability/regenerative-farming/arla_regenerative-farming-pilot-farm-network-brochure_english.pdf | Regenerative farming | -Sweden<br>-Denmark<br>-Germany<br>-the Netherlands<br>-UK | Dairy farming | No | Knowledge exchange | -Biodiversity<br>-Climate resilience<br>-Carbon sequestration<br>-Pollination<br>-Water (storage) |
| Farm:Carbon | https://farmcarbon.ie/ | Sustainable agriculture on peatlands | Ireland | Peatland agriculture | No | Knowledge exchange | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Flood control<br>-Water (storage & quality) |
| Sols de Bretagne | https://livelihoods.eu/fr/portfolio/bretagne-agriculture-regeneratrice/ | Agroecology | France (Bretagne) | Arable | No | Public funding | -Biodiversity<br>-Carbon sequestration |
| Beernem Carbon Farming | https://inagro.be/pers/koolstofbewustzijn-groeit-bij-gemeente-beernem-en-beernemse-landbouwers | Carbon sequestration | Belgium (Beernem) | Arable | No | Public funding (Free access to communal land) | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) |
| Klimaschutz durch Humusaufbau | https://www.baselland.ch/politik-und-behorden/direktionen/volkswirtschafts-und-gesundheitsdirektion/landw-zentrum-ebenrain/landwirtschaft/klimaschutz-durch-humusaufbau | Carbon sequestration | Switzerland (Kanton Basel) | All | No | Public funding | -Carbon sequestration |
| Resourcenprogramm Humus | https://so.humusbilanz.ch/ | Carbon sequestration | Switzerland (Kanton Soluthurn) | Arable | No | Public funding | Carbon sequestration |

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| Straw Incorporation Measure | https://www.gov.ie/en/service/86bd1-straw-incorporation-measure-sim/ | Carbon sequestration | Ireland | Arable | No | Public funding | Carbon sequestration |
| TerraPrima | https://www.terraprima.pt/en/area-de-actividade/1# | Carbon sequestration | Portugal | Grassland | No | Public funding | -Biodiversity<br>-Carbon sequestration |
| Verhogen van het effectieve organische koolstofgehalte van bouwland via het teeltplan | https://lv.vlaanderen.be/bedrijfsvoering/verzamelaanvraag/voorgaande-campagnes/verzamelaanvraag-2022/perceelsgebonden-pre | Carbon sequestration | Belgium (Flanders) | Arable | No | Public funding | Carbon sequestration |
| Catskills New York City Watershed | https://www.nycwatershed.org/about-us/overview/ | Drinking water protection | USA (New York) | All | No | Public funding | Water (supply & quality) |
| FRESP | https://sciences.ucf.edu/biology/bohlen/projects/florida-ranchland-environmental-services-project/ | Ecosystem services | USA (Florida) | Grassland | No | Public funding | Water (supply & quality) |
| Glastir | https://www.gov.wales/glastir-small-grants | Ecosystem services | UK (Wales) | All | No | Public funding | -Biodiversity<br>-Carbon sequestration<br>-Flood control<br>-Pollination<br>-Water (quality) |
| InVest | https://naturalcapitalproject.stanford.edu/software/invest | Ecosystem services | Worldwide | All | No | Public funding | -Biodiversity<br>-Carbon sequestration<br>-Erosion control (sediment retention)<br>-Flood control<br>-Pollination<br>-Water (supply & quality) |
| Sustainable Farming Incentive | https://www.gov.uk/government/collections/sustainable-farming-incentive-guidance#sustainable-farming-incentive:-full-scheme-information | Environmental sustainability | UK | -Arable<br>-Horticulture<br>-Grassland<br>-Moorland | No | Public funding | -Biodiversity<br>-Climate resilience (Carbon sequestration)<br>-Erosion control<br>-Water (quality) |
| Conservation Reserve Program | https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/index#:~:text=CRP% | Land conservation | USA | -Arable<br>-Grassland | No | Public funding | -Biodiversity<br>-Erosion control<br>-Water (quality) |

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| | 20is%20a%20land%20conservation,improve%20environmental%20health%20and%20quality. | | | | | | |
| Environmental Stewardship | https://www.gov.uk/guidance/environmental-stewardship | Payment for ecosystem services<br>Soil quality | UK (England) | All | No | Public funding | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control<br>Pollination<br>-Water (storage & quality) |
| De Beemster | https://www.greenportnhn.nl/nieuws/belonen-op-doelen-en-ruimte-voor-vakmanschap-als-sleutel-voor-toekomstbestendige-landbouw | Sustainability | the Netherlands (Noord-Holland) | Arable | No | Public funding | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) |
| BBM | https://www.vangoghnationalpark.com/nl/homepage/brabants-bodem/deelprojecten/brabantse-biodiversiteitsmonitor-melkveehouderij-bbm | Sustainable dairy farming | the Netherlands (Noord-Brabant) | -Arable<br>-Grassland | No | Public funding | -Biodiversity<br>-Carbon sequestration<br>-Pollination<br>-Water (storage & supply) |
| Duurzaam Boeren Drenthe | https://www.provincie.drenthe.nl/duurzaamboerendrenthe/ | Sustainable dairy farming | the Netherlands (Drenthe) | -Arable<br>-Grassland | No | Public funding | -Biodiversity<br>-Carbon sequestration |
| Duurzame Melkveehouderij Drenthe | https://www.duurzamemelkveehouderijdrenthe.nl/ | Sustainable dairy farming | the Netherlands (Drenthe) | -Arable<br>-Grassland | No | Public funding | -Biodiversity<br>-Carbon sequestration<br>-Pollination |
| Markemodel | https://de-vala.nl/glb-pilot-het-markemodel/ | Sustainable dairy farming | the Netherlands (Gelderland) | -Arable<br>-Grassland | No | Public funding | -Biodiversity<br>-Water (quality) |

## 3.2 Monitoring systems of existing business models and related programs in which soil health and ecosystem services are the main drivers

The business models and related programs listed in Table 3-1 were analyzed in more detail for their respective monitoring systems. Our interest in this regard primarily went out to the indicators used to assess and evaluate soil health and the soil-related ESS of interest, the method of data collection and assessment and the distinctions between qualitative and quantitative and activity- and results-based schemes. The information on the monitoring systems of the earlier discussed programs is presented in Table 3-2.

To have a better overview, we split the indicators into five broad classes: 1) farming practices, which are thought to ensure the provision of specific soil-related ESS, were used by the largest group of programs (63), 2) soil parameters, were used in 49 programs, 3) biodiversity (or biological) parameters, were used in 15 programs, 4) water parameters, were used in ten programs, and 5) crop parameters, which were used in eight programs. When only looking at the business models the balance fell strongly towards the soil parameters (38). This is mostly linked to the proportionally large number of carbon farming schemes that measure or model soil carbon stocks. Still, 27 business models made use of specific farming practices as indicators, while the number that used biodiversity (5), water (3) or crop (3) parameters was rather limited. An overview of all the indicators, found during our exploration of the existing business models and related programs in which soil health and soil-related ESS are the main driver, is presented in Table 3-3. It should be noted that many of the programs do not give a detailed description of their monitoring system and often keep the indicators unspecified. Some business models, like Soil Heroes, plainly state that they only make public their “ingredients” (i.e. indicators), not their “recipe” (i.e. quantifying methods). The four groups of measured indicators (i.e. soil, biodiversity, water and crop) all contained both precisely quantified and qualitatively estimated indicators (e.g. organic carbon content and visually assessed color for soil, the number of earthworms and the visually assessed environmental impact of pesticides for biodiversity, the concentration of specific pollutants and the subjectively assessed odor for water and crop yield and the visually assessed crop color for crop).

For the methods of data collection and assessment of the previously mentioned indicators, a distinction was made between the broad grouping of interviews, questionnaires, farm visits and the use of publicly available spatial data, which was used by 38 programs and 14 business models; the grouping of field sampling, lab analyses and field measurements, which was used by 40 programs and 26 business models; modelling, used in 19 programs and ten business models, and remote sensing, used in eight programs and seven business models. Most of the programs that

made use of models in their monitoring systems were carbon farming schemes (e.g. Carbon Farmers, which used the RothC model, and Soil Capital, which used the Cool farm tool).The results from these modelling runs were both used as direct indicator, with which to quantify the monetary reward, like for Nori (Soil Metric tool), or as a way to measure the potential results at the start of the scheme, which will be compared to the results of actual field measurements at the end of the scheme, like for Soil heroes (RothC model). There were also some non-carbon farming schemes that made use of modelling, like the water quality schemes of NutrientNet, Wessex Water Catchment Management and FRESP, and the sustainable farming schemes of Climate Farmers, TAPE, EFA calculator, InVest and DuurzaamBoerenDrenthe. In most instances remote sensing was utilized to monitor the continued implementation of the required sustainable farming practices, like in the carbon farming schemes AgreenaCarbon, BCarbon, Carbon Farmers and Soil Capital, the ESS scheme FarmFacts and the sustainable farming scheme Earthworm. However, we also found business models that utilize remote sensing to measure biomass production. This was done either as a direct indicator, like for Naturellement Popcorn in France, or indirectly as an input for the modelling of soil organic carbon sequestration, like for the carbon farming scheme Carbon Farmers.

The monitoring systems were further distinguished, based on whether the assessment was qualitative, quantitative or a combination of both. Qualitative assessment was defined as dependent on a subjective judgement or perception, while quantitative assessment was defined as the precise quantification of indicators. More programs made use of a quantitative (46) than a qualitative approach (34) or a combination of both (11). This predominance was even clearer for the business models, 29, 14 and 4 models using the respective models.

Action-based schemes offer farmers or landowners a reward for adopting specific farming practices. In results-based schemes the reward is contingent on achieving a pre-described result (Bartkowski et al., 2021). The scheme was classified as activity-based if the indicators were calculated with models that only use farming practices as input parameters (e.g. Cool Farm Tool model for Soil Capital). If the indicators were derived from modelling outcomes that require inputs from field measurements and/or laboratory analyses (e.g. the simple analytical model used by Carbon Action in Finland to estimate changes in soil carbon stock), the schemes were classified as results based. In total, 43 programs could be classified as activity-based, 27 as results-based and 22 as a combination of the two. A much larger proportion of the results-based (19) schemes could be defined as business models, compared to the activity-based schemes (21). Activity-based schemes are often preferred by farmers or landowners, because of their certainty of reward. Results-based schemes after all contain the possibility of farmers receiving different rewards for

the same actions (Zabel & Roe, 2009). Similarly, results-based schemes usually have a more costly monitoring system. However, results-based schemes do offer an enhanced sensitivity to local conditions and reward inventiveness and innovation (Bartkowski et al., 2021; Kleijn et al., 2011).

*Table 3-2: Summary of the monitoring systems used by the programs listed in Table 3-1.*

| Assessment tool | Mentioned soil-related ESS | Indicators | Method of data collection | Quantitative or qualitative | Activity- or results-based |
|---|---|---|---|---|---|
| Soil Association Exchange | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) | Unspecified soil, water & biodiversity parameters | -Questionnaire<br>-Field sampling & lab analyses | Quantitative | Results |
| Farm for Good | No information given | Agroecological farming practices | Interview | No information given | Activity |
| FarmFacts | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) | Humus formation | -Field sampling & lab analysis<br>-Remote sensing | Quantitative | Activity & results |
| Ecological Outcome Verification | -Biodiversity<br>-Carbon sequestration<br>-Water (storage) | -Ground cover<br>-Water infiltration<br>-Soil health<br>-Soil organic carbon stock | Field measurements, sampling & lab analyses | Quantitative & qualitative | Results |
| On the way to PlanetProof | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (quality) | Soil organic carbon<br>Sustainable farming practices | -Questionnaire<br>-Farm visit<br>-Modelling (OM balance) | Qualitative | Activity |
| Pour une Agriculture du Vivant | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & quality) | Regenerative farming practices | Questionnaire | Qualitative | Activity |
| LandvanWaard | -Biodiversity<br>-Carbon sequestration<br>-Pollination | Biodiverse landscape elements | Farm visit | Qualitative | Activity |
| Claire | Carbon sequestration | -Farming practices<br>-Soil carbon content | -Questionnaire<br>-Soil sampling & lab analysis | Quantitative | Activity & results |
| AgreenaCarbon | -Biodiversity<br>-Carbon sequestration | Soil organic carbon stock | -Field sampling & lab analysis<br>-Farm visit<br>-Satellite imagery | Quantitative | Results |
| CarboAgrar | -Carbon sequestration<br>-Erosion control<br>-Water (storage) | Weight of CO2 sequestered | Field sampling & lab analysis | Quantitative | Results |

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|---|---|---|---|---|---|
| Carbon Farmers | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Flood control<br>-Water (storage & quality) | -Carbon balance<br>-Carbon sequestration potential | -Field sampling & lab analysis<br>-Satellite imagery<br>-Modelling | Quantitative | Activity & results |
| Carboneg | -Biodiversity<br>-Carbon sequestration | Weight of CO2 sequestered | -Field sampling & lab analysis<br>-Modelling (RothC) | Quantitative | Results |
| CO2-land | -Carbon sequestration<br>-Climate resilience<br>-Biodiversity<br>-Water (storage & quality)<br>-Erosion control<br>-Flood control | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Dutch Carbon Credits | Carbon sequestration | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Indigo | -Carbon sequestration | Soil organic carbon balance | -Modelling (DayCent)<br>-Field sampling & lab analysis | Quantitative | Activity & results |
| Klim.eco | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control | Regenerative farming practices | No information given | Qualitative | Activity |
| Nori | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Flood control<br>-Water (storage & quality) | Weight of CO2 sequestered | Modelling (Soil Metrics tool) | Quantitative | Activity |
| Positerra | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) | Weight of CO2 sequestered | Field sampling & lab analysis | Quantitative | Results |
| Rabo Carbon bank | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & quality) | Potential carbon sequestration | Modelling | Quantitative | Activity |
| Svensk Kolinlagring (Swedish carbon storage) | -Biodiversity<br>-Carbon sequestration | -Soil organic carbon stock<br>-Soil structure (Spade test)<br>-Biodiversity | Field sampling & lab analysis | Quantitative & qualitative | Results |

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| | -Climate resilience<br>-Water (storage) | -Water infiltration | | | |
| Wisber EU | -Carbon sequestration<br>-Water (storage) | Weight of CO2 sequestered | Field sampling & lab analysis | Quantitative | Results |
| CAR Soils | Carbon sequestration | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| BCarbon | Carbon sequestration | Soil organic carbon stock | -Field sampling & lab analysis<br>-Remote sensing | Quantitative | Results |
| CarboCert | -Biodiversity<br>-Carbon sequestration<br>-Water (quality)<br>-Erosion control | Weight of CO2 sequestered | Field sampling & lab analysis | Quantitative | Results |
| Humus+<br>Modell Ökoregion Kaindorf | -Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Soil Capital | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience | Weight of CO2 sequestered | -Questionnaire<br>-Modelling (Cool farm tool)<br>-Satellite imagery | Quantitative | Activity |
| Windpark Krammer | -Carbon sequestration<br>-Water (storage) | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Zukunft Erde | Carbon sequestration | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Cool Crowd project | Carbon sequestration | Application of biochar | No information given | Qualitative | Activity |
| Agrivair (Vittel) | -Biodiversity<br>-Water (supply & quality) | Sustainable farming practices | No information given | Qualitative | Activity |
| APIEME | -Biodiversity<br>-Water (supply & quality) | Regenerative farm practices | No information given | Qualitative | Activity |
| DWPS | Water (quality) | Water catchment sparing/protecting practices | Farm visit | Qualitative | Activity |
| SCaMP | -Biodiversity<br>-Water (quality) | Water catchment sparing/protecting practices | No information given | Qualitative | Activity |
| Wessex Water Catchment Management | -Biodiversity<br>-Water (quality) | -Environmental farming practices<br>-Soil nitrate residue<br>-Surface water pesticide contamination | -Interview<br>-Farm visit<br>-Field & water sampling & lab analysis<br>-Modelling | Quantitative & qualitative | Activity & results |
| Naturellement Popcorn | -Biodiversity<br>-Carbon sequestration | Biomass production cover crops | Satellite imagery | Quantitative | Results |

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| | -Climate resilience<br>-Erosion control<br>-Water (quality) | | | | |
| OleoZE | -Carbon sequestration | Sustainable farming practices | No information given | Qualitative | Activity |
| BEF Water Certificates | -Biodiversity<br>-Water (supply & quality) | Water saving practices | No information given | Quantitative | Activity |
| Slowing the flow at Pickering | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control | Farming practices that reduce the risk of flooding | Farm visit | Qualitative | Activity |
| Upstream Thinking | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control<br>-Water (quality) | Environmental farming practices | -Interview<br>-Farm visit | Qualitative | Activity |
| Pumlumon Project | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>+Flood control<br>-Water (storage & quality) | Farming practices that provide ecosystem services:<br>-Ditch blocking<br>-Hardwood tree planting<br>-Changes in grazing management<br>Unspecified habitat & hydrological parameters | Field measurements, sampling & lab analysis | Qualitative & quantitative | Activity & results |
| Verified carbon standard | -Biodiversity<br>-Carbon sequestration<br>-Additional (claimed but not specified) | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Climate farmers | -Carbon sequestration<br>-Climate resilience<br>-Water (storage) | Weight of CO2 sequestered | -Modelling<br>-Satellite imagery | Quantitative | Activity |
| Danone | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage) | Regenerative farming practices | No information given | Qualitative | Activity |
| Nestlé | -Biodiversity<br>-Carbon sequestration | -Soil organic carbon content<br>-Regenerative farming practices | -Questionnaire<br>-Field sampling & lab analysis | Quantitative | Activity & results |

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| | -Climate resilience<br>-Water (storage & quality) | | | | |
| Soil Heroes | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & regulation) | -Penetration resistance<br>-Bulk density<br>-In-depth volumetric moisture content (TDR)<br>-Texture<br>-Horizon depth<br>-Earthworms<br>-Soil respiration (CO2 concentration)<br>-Active carbon<br>-Nutrient levels<br>-Organic carbon content<br>-Ground cover<br>-Cropping plan<br>-Plot history<br>-Fertilization<br>-Tillage<br>-Yields<br>-Soil organic carbon stock | -Field measurements, sampling & lab analysis<br>-Modelling (RothC) | Quantitative | Activity & results |
| Earthworm - Living Soils Project | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & regulation) | Unspecified physical, chemical & biological soil parameters | -Field measurements & sampling<br>-Satellite imagery | Quantitative | Results |
| NutrientNet | Water (quality) | Farming practices that reduce nutrient application | Modelling | Quantitative | Activity |
| Westcountry angling Passport | -Biodiversity<br>-Water (quality) | Unspecified farming practices | No information given | Qualitative | Activity |
| GTAE | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) | -Soil surface status<br>-Water infiltration<br>-Structural status of soil<br>-Stability of aggregates<br>-Status of decomposition of plant residues and of macrofaunal activity | Field measurements, soil sampling & lab analyses | Quantitative | Activity & results |

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| | | -Mesofauna activity<br>-Organic matter status<br>-Quantity and availability of nutrients for plants<br>-Chemical constraints of nutrient availability in soils<br>-Diversity and abundance of harmful or useful macroinvertebrates<br>-Average rate of soil carbon sequestration | | | |
| OASIS | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control<br>-Pollination<br>-Water (storage & quality) | Agroecological farming practices | -Interview<br>-Farm visit | Qualitative | Activity |
| TAPE | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) | -Soil structure<br>-Degree of compaction<br>-Soil depth<br>-Status of residues<br>-Color, odor and organic matter<br>-Water retention<br>-Soil cover<br>-Signs of soil erosion<br>-Presence of invertebrates<br>-Microbiological activity | -Interview<br>-Field measurements<br>-Modelling | Quantitative | Activity & results |
| GAIA biodiversity yardstick | Biodiversity | (Agro-) biodiversity on farm | Questionnaire | Qualitative | Activity |
| Agrinewal | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) | Combination of farming practices & unspecified soil & biodiversity parameters | Field measurements & lab analyses | Quantitative | Activity & results |
| World-Climate Farm Tool | Carbon sequestration | Carbon balance | Modelling (World-Climate Farm tool) | Quantitative | Activity |
| EFA Calculator | -Carbon sequestration<br>-Erosion control | Presence of semi-natural habitats | Modelling | Quantitative | Activity |

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| | -Flood protection<br>-Global climate regulation<br>-Pest control<br>-Water (supply, regulation & quality) | | | | |
| Global farm metric | -Biodiversity<br>-Carbon sequestration<br>-Water (storage & quality) | Unspecified soil & water parameters | No information given | Qualitative | Results |
| IDEA | -Pollination<br>-Water (storage & quality) | Sustainable farming practices | Interview | Qualitative | Activity |
| LEAF Sustainable Farming Review | -Carbon sequestration<br>-Erosion control<br>-Global climate regulation<br>-Water (supply, regulation) | -Soil structure (VSA)<br>-Drainage<br>-Water movement<br>-Topsoil compaction<br>-Subsoil compaction<br>-Soil organic matter status<br>-Soil pH<br>-Nutrient status (P & K)<br>-Earthworms<br>-Living organisms<br>-Smell<br>-Plant residues | Field measurements | Qualitative | Results |
| Origin Green | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) | Carbon footprint | -Interview<br>-Modelling | Quantitative | Activity |
| RISE | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (storage & quality) | Farming practices | -Interview<br>-Farm visit | Qualitative | Activity |
| SAFA | -Biodiversity<br>-Carbon sequestration<br>-Flood control<br>-Landslide control<br>-Pollination<br>-Water (storage & quality) | -Greenhouse gas emission reduction target<br>-Greenhouse gas mitigation practices<br>-Greenhouse gas balance<br>-Air pollution reduction target<br>-Air pollution prevention practices | -Interview<br>-Field measurements, sampling & lab analyses | Qualitative & quantitative | Activity & results |

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| | | -Ambient concentration of air pollutants<br>-Water conservation target<br>-Water conservation practices<br>-Ground & surface water withdrawals<br>-Clean water target<br>-Water pollution prevention practices<br>-Concentration of water pollutants<br>-Wastewater quality<br>-Soil improvement practices<br>-Soil physical structure<br>-Soil chemical quality<br>-Soil biological quality<br>-Soil organic matter<br>-Land conservation and rehabilitation plan<br>-Land conservation and rehabilitation practices<br>-Net loss/gain of productive land<br>-Landscape/marine habitat conservation plan<br>-Ecosystem enhancing practices<br>-Structural diversity of ecosystems<br>-Ecosystem connectivity<br>-Land use and land cover change<br>-Species conservation target<br>-Species conservation practices<br>-Diversity and abundance of key species<br>-Diversity of production<br>-Wild genetic diversity enhancing practices | | | |

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| | | -Agro-biodiversity in-situ conservation<br>-Locally adapted varieties and breeds<br>-Genetic diversity in wild species<br>-Saving of seeds and breeds<br>-Material consumption practices<br>-Nutrient balance<br>-Renewable and recycled materials<br>-Intensity of materials used<br>-Renewable energy use target<br>-Energy saving practices<br>-Energy consumption<br>-Renewable energy<br>-Waste reduction target<br>-Waste reduction practices<br>-Waste disposal<br>-Food loss and waste reduction<br>-Animal health practices<br>-Animal health<br>-Humane animal handling practices<br>-Appropriate animal husbandry<br>-Freedom from stress | | | |
| SAFE | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) | <u>Ecosystem integrity:</u><br>-Ratio of net radiation flux and incoming net solar radiation<br>-Free net primary biomass productivity<br><u>Air:</u><br>-Greenhouse gases emissions<br>-Indirect CO2 emissions due to the use of synthetic N fertilizers<br>-Ammonia emission<br>-Pesticide Risk Score to air | No information given | Qualitative | Activity & results |

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| | | -Land use pattern<br><u>Soil:</u><br>-Water erosion risk<br>-Harvest erosion<br>-Tillage erosion risk<br>-Soil analysis (organic C, N and P soil content, pH)<br>-Pesticide residues<br>-Nitrogen, Phosphorus and Potassium Annual Balance<br>-Addition of heavy metals<br>-Soil organic carbon balance<br>-Tillage pressure<br>-Compaction risk<br><u>Water:</u><br>-Surface water balance<br>-Irrigation practices<br>-Drought stress<br>-Groundwater level<br>-Water consumption<br>-Pesticide runoff risk<br>-Presence of grass strips/riparian areas<br>-Pesticide residues<br>-Vegetation cover during nitrate leaching period<br>-Good agricultural practices<br>-Soil link rate<br>-Potentially leachable nitrogen<br>-Nitrogen System Balance<br>-Runoff risk<br>-Soil cover index<br>-Vegetation cover<br>-Presence of grass strips/riparian areas<br><u>Energy:</u> | | | |

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|---|---|---|---|---|---|
| | | -Direct energy output<br>-Direct energy input<br>-Renewable direct energy input<br>-Energy balance<br><u>Biodiversity:</u><br>-Number of crop species<br>-Number of threatened rare crop varieties<br>-Number of livestock species<br>-Number of threatened and rare livestock breeds<br>-Total number of wild plant species in permanent grassland<br>-Soil biological activity<br>-Earthworm species saturation<br>-Butterfly species saturation<br>-Number of protected and red list butterfly species<br>-Breeding bird species saturation<br>-Number of protected and red list bird species<br>-Number of European Bird Directive species<br>-Wild flora species saturation<br>-Number of protected and red list wild flora species<br>-Total number of wild plant species in permanent grassland<br>-Pesticide Risk Score to biodiversity<br>-Fertilizer pressure on Natura 2000 grasslands<br>-Proportion of high biological value meadows in permanent grassland | | |

| | | | | | |
|---|---|---|---|---|---|
| | | -Existence of special devices for wild fauna<br>-Habitat saturation<br>-Agricultural area under management contract<br>-Agricultural area managed for wild biota without management contract<br>-Agricultural area under organic farming contract<br>-Density of linear landscape elements<br>-Connectivity index of linear landscape elements | | | |
| SMART | No information given | Sustainable farming practices | Interview | Qualitative | Activity |
| Genesis | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) | -Biodiversity score<br>-Climate score<br>-Water quality score<br>-Fertility score<br>-Environmental impact score | Field sampling & lab analysis | Quantitative | Activity & results |
| Openbodemindex | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Water (quality)<br>-Water (supply, infiltration, retention) | Unspecified soil parameters (data from soil analyses are used in a model, "Rekenhart", to calculate a list of soil health indicators) | -Field sampling & lab analysis<br>-Modelling | Quantitative | Results |
| Ecoplan | -Carbon sequestration<br>-Erosion control<br>-N storage<br>-P storage<br>-Water (supply, infiltration, retention) | Farming practices | Spatial data | Qualitative | Activity |
| Ecosystems Flanders | -Erosion control<br>-Flood control<br>-Water (supply, quality regulation) | Farming practices | Spatial data | Qualitative | Activity |

| | | | | | |
|---|---|---|---|---|---|
| MAES | -Carbon sequestration<br>-Flood control | -Carbon sequestration<br>-Land use & cover<br>-Slope<br>-Hydraulic properties | Spatial data | Quantitative | Activity & results |
| LIFE Viva Grass | -Bioremediation by micro-organisms, plants and animals<br>-Chemical condition of freshwaters<br>-Erosion control<br>-Filtration, storage & accumulation of nutrients<br>-Global climate regulation<br>-Maintaining habitats<br>-Pollination and seed dispersal<br>-Provision of cultivated crops<br>-Provision of reared animals and their outputs<br>-Provision of fodder<br>-Provision of Biomass-based energy sources<br>-Provision of herbs for medicine<br>-Weathering processes/soil fertility | -Grassland management practices<br>-Land use<br>-Land quality<br>-Slope | Spatial data | Qualitative | Activity |
| Bloemenstroken voor meer biodiversiteit (Tiense Suiker) | -Biodiversity<br>-Carbon sequestration<br>-Pollination<br>-Water (quality) | Sowing of flower strips on the edge of sugar beet fields | No information given | Qualitative | Activity |
| Carbon action | -Biodiversity<br>-Carbon sequestration | Soil organic carbon stock | Field sampling & lab analysis | Quantitative | Results |
| Arla's Regenerative Farming Pilot Network | -Biodiversity<br>-Climate resilience<br>-Carbon sequestration | -Soil health indicators<br>-Biodiversity indicators<br>-Ecosystem process assessments | -Field measurements, sampling & lab analyses | Qualitative | Results |

| | | | | | |
|---|---|---|---|---|---|
| | -Pollination<br>-Water (storage) | | | | |
| Farm:Carbon | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Flood control<br>-Water (storage & quality) | -Peatland farming practices<br>-Unspecified soil, water & biodiversity parameters | -Farm visit<br>-Field measurements | Quantitative | Activity & results |
| Sols de Bretagne | -Biodiversity<br>-Carbon sequestration | Regenerative farming practices | No information given | Qualitative | Activity |
| Beernem Carbon Farming | -Biodiversity<br>-Carbon sequestration<br>-Climate resilience<br>-Erosion control<br>-Water (storage & quality) | Carbon sequestration promoting practices | -Interview<br>-Farm visit | Qualitative | Activity |
| Klimaschutz durch Humusaufbau | -Carbon sequestration | Soil organic carbon stock | Soil sampling & lab analysis | Quantitative | Results |
| Resourcenprogramm Humus | Carbon sequestration | Humus balance | Modelling (Humus balance calculator) | Quantitative | Activity |
| Straw Incorporation Measure | Carbon sequestration | Incorporation of straw | Questionnaire | Qualitative | Activity |
| TerraPrima | -Biodiversity<br>-Carbon sequestration | Crop rotation | Field sampling & lab analysis | Quantitative | Results |
| Verhogen van het effectieve organische koolstofgehalte van bouwland via het teeltplan | Carbon sequestration | Soil organic carbon stock | Questionnaire | Quantitative | Activity |
| Catskills New York City Watershed | Water (supply & quality) | Farming practices that reduce diffuse pollution of the water supply | Interview | Qualitative | Activity |
| FRESP | Water (supply & quality) | -Phosphorus content<br>-Water retained in wetlands, ditches or soil profile | -Field measurements<br>-Modelling | Quantitative | Results |
| Glastir | -Biodiversity<br>-Carbon sequestration<br>-Flood control | Farming practices | -Field visit<br>-Questionnaire | Qualitative | Activity |

| | | | | | |
|---|---|---|---|---|---|
| | -Pollination<br>-Water (quality) | | | | |
| InVest | -Biodiversity<br>-Carbon sequestration<br>-Erosion control (sediment retention)<br>-Flood control<br>-Pollination<br>-Water (supply & quality) | Land use & cover | Modelling | Quantitative | Activity |
| Sustainable Farming Incentive | -Biodiversity<br>-Climate resilience (Carbon sequestration)<br>-Erosion control<br>-Water (quality) | -Application of organic matter to soil<br>-Green cover during winter<br>-Minimize bare soil<br>-Herbal leys<br>-Texture<br>-Soil structure & compaction<br>-Soil biology)<br>-Assessment of risk to runoff & erosion (gradient slope, slope length, soil texture, flooding frequency, history of runoff and ponding, distance to water, soil organic carbon content, land-use, soil structure)<br>-Soil organic carbon content | -Field sampling & lab analysis<br>-Remote sensing | Quantitative & qualitative | Activity & results |
| Conservation Reserve Program | -Biodiversity<br>-Erosion control<br>-Water (quality) | Removal of environmentally sensitive land from agricultural production and establishing long-term, resource-conserving cover | Questionnaire | Qualitative | Activity |
| Environmental Stewardship | -Biodiversity<br>-Carbon sequestration<br>-Erosion control<br>-Flood control<br>Pollination<br>-Water (storage & quality) | Environmental farming practices | -Questionnaire<br>-Farm visit | Qualitative | Activity |

| | | | | | |
|---|---|---|---|---|---|
| De Beemster | -Biodiversity<br>-Carbon sequestration<br>-Water (quality) | -Origin inputs<br>-Soil quality<br>-SOC content<br>-Energy balance<br>-Use pesticides<br>-Nature & landscape elements | Questionnaire | Quantitative & qualitative | Activity & results |
| BBM | -Biodiversity<br>-Carbon sequestration<br>-Pollination<br>-Water (storage & supply) | -% of permanent grassland<br>-% protein from own soil<br>-N surplus<br>-Greenhouse gas emissions<br>-Ammonia emissions<br>-% natuurbeheersland<br>-% of herb-rich grassland<br>-Use pesticides<br>-Use mineral fertilizers<br>-Days of grazing<br>-Protein in total fodder gift | Questionnaire | Quantitative & qualitative | Activity & results |
| Duurzaam Boeren Drenthe | -Biodiversity<br>-Carbon sequestration | -Ammonia emission<br>-Days of grazing<br>-Crude protein in fodder<br>-% of protein from own soil<br>-Crop rotation index (0-1)<br>-Environmental impact pesticides<br>-Phosphate surplus<br>-Carbon balance<br>-N surplus<br>-Greenhouse gas emissions | -Questionnaire<br>-Modelling (Carbon balance) | Quantitative & qualitative | Activity & results |
| Duurzame Melkveehouderij Drenthe | -Biodiversity<br>-Carbon sequestration<br>-Pollination | -Greenhouse gas emissions<br>-Phosphate surplus<br>-Nitrogen surplus<br>-Ammonia emission<br>-% of protein from own soil<br>-% of permanent grassland<br>-Days of grazing<br>-Sustainable energy production<br>-% certified soya | Questionnaire | Quantitative & qualitative | Activity & results |

| | | | | | |
|---|---|---|---|---|---|
| | | -% area nature & landscape elements | | | |
| Markemodel | -Biodiversity<br>-Water (quality) | -Greenhouse gas emissions<br>-Ammonia emissions<br>-Water quantity<br>-N surplus<br>-Phosphorus surplus<br>-Environmental impact locations<br>-% of land with beheerspakket<br>-% of herb-rich grassland<br>-% of protein from own soil | Questionnaire | Quantitative & qualitative | Activity & results |

*Table 3-3: Overview of the indicators used by the business models and related programs, which were presented in Table 3-2.*

| | | |
|---|---|---|
| ***Soil parameters*** | | |
| Greenhouse gas balance | Clay content | Stability of aggregates |
| Ammonia emission | Clay type | Bulk density |
| Soil organic carbon content | Concentration of micronutrients | Topsoil compaction level (visual assessment) |
| Soil organic carbon stock | Penetration resistance | Concentration of heavy metals |
| Carbon balance | Visual assessment soil structure (Spade test) | Soil depth |
| Horizon depth | Slope length | Salinity |
| Color (visual assessment) | Soil cover (visual assessment) | Soil surface status (visual assessment) |
| Odor (Subjective assessment) | Signs of erosion (visual assessment) | Subsoil compaction level (visual assessment) |
| Status of crop residues | Concentration of nitrogen | Nitrogen surplus |
| Slope gradient | pH | Concentration of phosphorus |
| Phosphate surplus | Water infiltration | Groundwater level |
| Concentration of Potassium | Available water capacity | Water content |
| Texture | | |
| ***Biodiversity parameters*** | | |
| Diversity of key species | Number of insects | Habitat saturation |
| Number of earthworms | Number of bird species | Activity of micro-organisms |
| Earthworm saturation | Breeding bird saturation | Wild flora saturation |
| Presence of metabolic substances | Number of protected flora species | Environmental impact pesticides (Visual assessment) |
| ***Water parameters*** | | |
| Concentration of water pollutants | Presence of bacteria | Odor (Subjective assessment) |
| Water conductivity | Flooding frequency | Amount of water retained in fields |
| Water density | Standing water (Visual assessment) | Phosphorus content |
| ***Crop parameters*** | | |

| | | |
|---|---|---|
| Crop growth (Visual assessment) | Crop color (nutrient availability) (visual assessment) | Crop yield |
| Vegetation cover | | |
| *Farming practices* | | |
| Crop rotation (e.g. no maize, deep rooting fodder crops - alfalfa & clover species) | Water conservation measures (e.g. drip irrigation, rainwater harvesting) | Landscape elements (e.g. hedgerows, ponds, in-field trees) |
| Cover crops | Grazing livestock | Buffer strips |
| Agroforestry | Certified soya fodder | Rewetting |
| Tillage method (e.g. contour ploughing, reduced tillage) | Managing livestock access to water courses (e.g. fencing) | Loosening compacted soil layers (e.g. subsoiling) |
| Land use | Mixed stocking | Ground cover |
| Agrobiodiversity | Grazing management | Nutrient management plan |
| Diverse varieties | Grass swales | Compost application |
| Erosion control measures (e.g. hardening of livestock gathering points, managing over-winter tramlines, undersowing) | Removal of environmentally sensitive land from production | (Reduced or altered) pesticide use |
| Habitats for biodiversity | Livestock watering | Leaving crop residue on field |
| Reduced livestock density | Check dams | |
| Pesticide sprayer loading area | Organic manure | Haymaking |
| Biobed | Bee keeping | Tree planting |
| Fixing water course banks with native vegetation | (Reduced or altered) fertilizer use | Stimulating natural (rough) vegetation |
| Biofilter | Fallow headlands | Peatland restoration |
| Flower strip | Overwintered stubble | Heather restoration |
| Permanent biodiverse grassland | Fodder production in own fields | Flood control measures |
| Beetle banks | Cereal headlands for birds | Bird seed mixtures |

# 4. Technologies for Measurement and Management

This chapter provides a catalogue of options for the communities of practices and testing grounds to inform subsequent tasks and work packages. The lists below are far from complete but serve as a compilation to inspire the testing grounds. Once the topics of these testing grounds are selected, a further review of technologies, remote sensing services, sensor and data sharing initiatives should be carried out.

## 4.1 Technologies for soil-based ecosystems services or proxies

The services and/or proxies can be divided into parameters directly related to soil-based parameters, i.e. soil organic carbon, electrical conductivity, pH, soil moisture, bulk density, or indirectly related through crop and environmental parameters, i.e. soil cover, crop yield, overall biomass, greenhouse gases, etc. The following table provides an overview of some of the available services and proxies that could be used within the project. A selection was made in Table 4-1 to highlight the different technologies, sensors and platforms. A more complete list of sensors and applications was developed through Smart-AKIS (H2020 grant agreement 696294), SmartAgriHubs (H2020, 818182) and IOF2020 (H2020, 731884). Readers looking for a more complete list of available technologies and sensors at various TRL levels could use the databases developed by these projects, e.g. Smart Farming Platform.

*Table 4-1: Overview of examples for services or proxies for soil-related ecosystem evaluation that can be monitored and measured through technology. A depiction of the current availability as a service (AAS) is also provided*

| Service | Technology | Sensor(s) | Platform (availability) | Source | Notes |
|---|---|---|---|---|---|
| SOC | Soil scanner | Veris MSP3 | *Tractor (AAS)* | https://www.veristech.com | Through spectral information, calibration through soil samples for each parcel |
| | Soil sensor | AgroCares Nutrient scanner | Handheld (AAS) | https://www.agrocares.com/soilcares/ | Soil parameters estimation based on spectral information for calibrated countries |
| | Remote sensing | Sentinel-2, Landsat 7/8 | Satellite | (Zhou et al., 2022) | Soil organic carbon mapping at field scale, calibrated for Belgium |
| | Remote sensing | Sentinel-2 | Satellite | https://envision-h2020.eu/ | Large scale monitoring of farm management activities |

| | | | | | |
|---|---|---|---|---|---|
| | Remote sensing | MicaSense | Drone | (Biney et al., 2021) | Mapping on small scale dataset |
| pH | Soil scanner | Veris MSP3 | Tractor (AAS) | | Contact probe, calibration through soil samples for each parcel |
| | Soil sensor | AgroCares Nutrient scanner | Handheld (AAS) | | Soil parameters estimation based on spectral information for calibrated countries |
| EC | Soil scanner | Veris MSP3 | Tractor (AAS) | | Contact probe, calibration through soil samples for each parcel |
| | Soil scanner | Dualem 21s | Tractor (AAS) | https://www.soilmasters.com/<br><br>https://dualem.com/products/ | Conductivity without contact with soil. Calibration with soil samples to obtain other soil parameters. |
| Soil moisture | Soil sensor | Pessl Metos, FieldMate, TerraSen | (AAS) | https://www.fieldclimate.com/<br>https://smartfarm.nl/en/sensors-en/<br>https://www.dacom.nl/nl/ | Point measurement to continuously monitor rainfall, temperature, soil moisture, etc. linked with data platform and retrievable with APIs |
| | Soil sensor | Sensoterra, Farm21, SensorBox | (AAS) | https://www.sensoterra.com/<br>https://www.farm21.com/<br>https://www.agroplanning.com/nl/ | Point measurement to monitor soil moisture, temperature linked with data platform and retrievable with APIs |
| | Remote sensing | Radar | Satellite | (Bastiaanssen et al., 2005; de Jeu et al., 2008) | Radar images to visualize spatial distribution of soil moisture (shallow) |
| Bulk density | Remote sensing | ASD and gamma-ray | Lab/Handheld | (Lobsey & Viscarra Rossel, 2016) | Gamma ray estimation and correction for water content through vis-NIR spectroscopy |
| Soil cover | Remote sensing | Sentinel-2 | Satellite | https://terrascope.be/en/sectors/agriculture | Estimation of cover without distinction between crops and weeds, calibrated for Belgium and the Netherlands |
| Crop yield | Yield measurement | Mass flow sensor | Tractor (AAS) | https://www.deere.com/en/agriculture/ | Flow sensor for combines, retrievable through APIs |

| | | | | | |
|---|---|---|---|---|---|
| | Remote sensing | HarvestLab | Tractor (AAS) | https://www.deere.com/en/agriculture/ | Spectral measurement of total yield and dry matter, calibration per crop |
| | Remote sensing | Sentinel-2 | Satellite (AAS) | https://watchitgrow.be/en (Piccard et al., 2017) | Potato yield estimation, calibrated for Belgium |
| | Remote sensing | MicaSense, RGB | Drone (AAS) | https://mapeo.vito.be/en | Yield mapping through flower counting, fruit counting, flowering intensity and plant vigor |
| | Yield measurement | | Tractor | | Weight sensor for harvesters, retrievable through APIs |
| Biomass | Remote sensing | Sentinel-2 | Satellite | https://watchitgrow.be/en https://www.dacom.nl/nl/ https://www.agremo.com/products/crop-monitoring/ | Spatial distribution of greenness (NDVI) within one parcel |
| | Remote sensing | Isaria, Greenseeker, OptRx, N-sensor, etc. | Tractor | (Pallottino et al., 2019) | Crop sensor estimation based on NDVI, no distinction between weed/crop |
| | Remote sensing | | Drone | (Haumont et al., 2022; Wang et al., 2021) | Crop biomass monitoring calibrated for various crops |
| Greenhouse gases | Remote sensing | IASI | Satellite | (Van Damme et al., 2018) | Ammonia point source detection |
| | Remote sensing | Sentinel-5P | Satellite | (Sha et al., 2021) | Methane and carbon monoxide on a regional scale |
| | Remote sensing | Aeris MIRA | Drone | (Gålfalk et al., 2021) | Spectral detection of methane, requires before flight and onboard calibrations |
| | Remote sensing | AlphaSense, Aerocet, COCAP | Drone | (Jońca et al., 2022) | Drone sniffing with various sensors |
| Crop classification | Remote sensing | Sentinel-1, Sentinel-2 | Satellite | (Van Tricht et al., 2018) | Time series analysis and classification, calibrated for Belgium |

| | | | | | |
|---|---|---|---|---|---|
| Land use | Remote sensing | Sentinel-1, Sentinel-2 | Satellite | https://zenodo.org/record/7254221 | Global land use product at 10 m resolution |
| Farmer activity | Farm Management Systems | | Watchitgrow, Agroplanning, MyJohnDeere, Dacom, AVRConnect. (AAS) | | Farm management software to register operations |
| | Crop map | | | https://arxiv.org/pdf/2302.10202.pdf | Eurocrops dataset, available map of agricultural parcel and crops/use |
| | Remote sensing | Sentinel-1 | Satellite | (Voormansik et al., 2020) | Mowing/plowing events through time series analysis |

## 4.2 Knowledge of available and promising sensors

Most of the technologies and sensors described in Table 4-1 are still under development, have to be calibrated for application in other regions and/or need to be standardized. They all have the potential to develop into a regionally applied system to monitor soil-related ESS, albeit at a big variety of costs, e.g. drone imaging mission versus satellite monitoring. On the other hand, some sensors are already widely available as a monitoring service and are supported by local governments, e.g. Veris/Dualem soil scanning and yield measurements.

When selecting a sensor, technology or platform, a variety of parameters must be accounted for that could play a role for each application. For instance, all remote sensing platforms have a distinctive **spatial, spectral and temporal resolution** and each application will require another set of resolutions. For example, satellite platforms are available on a global scale but have a limited spatial resolution or a limited temporal resolution, on the other hand tractor or drone mounted sensors have a high spatial resolution but have a limited spectral resolution and are limited to local monitoring campaigns. The large benefit of using remote sensing platforms and more specifically satellite platforms for ESS is the capabilities towards continuous monitoring over longer time and spatial scales. The mapping and revisit capabilities of these satellite platforms offer inputs for both seasonal and long-term monitoring studies on a local and regional scale (Weiss et al., 2020).

The application or availability of services could also be hampered by conditions, limitations or restrictions on field or regional scales. On a field scale, the estimation of soil parameters through

remote sensing often requires a **bare soil** and therefore is only available in small time frames within a growing season. The increased use of green manure and cover crops further limits the availability of an estimation with remote sensing technologies. Moreover, ESS dependent on optical satellite imagery (e.g. Sentinel-2) are hampered by **clouds**. The obstruction by clouds was found to be between 60 and 85% in western Europe (Teuling et al., 2017) and between 59 and 72% in eastern Europe (Sîcă et al., 2021). Some methods have successfully used a combination of optical and radar sensors to circumvent this (Van Tricht et al., 2018). In addition, the estimation of soil-related ESS requires correction for different crops and/or different cultivars, e.g. soil parameters, yield estimation. Finally, crop residues will have an influence on the estimation of soil parameters through remote sensing and should be accounted for, e.g. soil organic carbon (Dvorakova et al., 2020).

On a regional scale, soil-related ESS are limited by the availability of **specific calibrations** for each country (e.g. AgroCares nutrient sensor, soil organic carbon mapping through satellite platforms (Zhou et al., 2022)), as a result of researchers being geographically limited by regional funding and local service providers. In addition, some of the available sensor platforms are limited due to different drone **legislation** restrictions and geo-zones for different countries. An overall European drone legislation (2019/947 and 2019/945) is making it easier to fly across Europe, although flying altitude, weight and safety restrictions, which could limit widespread use.

## 4.3 Data support systems for collecting farm activity data and model inputs and data sharing initiatives

The different data support systems for exchange of relevant data were mapped. In Table 4-2 a non-exhaustive list of examples is provided.

*Table 4-2: Overview of examples data support systems and data sharing initiatives for exchange of data relevant to soil-related ESS*

| Data support system and sharing initiatives | Region * | Notes |
|---|---|---|
| Agdatahub | Europe | Data protection and secure data exchange |
| Agrirouter | Europe | Interface to connect and share agricultural machinery data with software solutions |
| Atlas | Europe | Project developing an open interoperability network for agricultural applications and to build up a |

| | | |
|---|---|---|
| | | sustainable ecosystem for innovative data-driven agriculture |
| Care4Growing | B | Management system for open field and greenhouses, linked with legislation, warning systems and advisory portal |
| Data Agri | Fr | Data collection, traceability, carbon footprint |
| Demeter | Europe | Project extracting knowledge from existing platforms and machinery |
| Divine | Europe | Project harnessing data economy for crop production through crop yield modelling and data integration between farm management software systems |
| DjustConnect | B | Administrative simplification by data sharing. Improved decision making for crops, livestock, carbon footprint and sustainability applications |
| FieldScout | B, N, G, Fr, S | Service platform to make data-driven decisions through crop monitoring and soil mapping |
| Mapeo | Europe | Processing drone images to provide yield mapping, flower/fruit counting, flowering intensity and plant vigor |
| Numagri | Fr | Support traceability and logistics in arable farming to reduce environmental impact by streamlining data flows |
| Soil Passport/Bodempaspoort | B | Digital tool for data driven soil management, aimed at collecting and presenting soil related data about an agricultural parcel |
| Taakkaart | B, N, G | Web application to monitor and manage parcels and manage machinery through sensors, gps and satellite imagery |
| Tritom | Fi | Data ecosystem to share crop planning, accounting, tractor and silos throughout the supply chain |
| Watchitgrow | B, N, Fr | Farm management software to register farm operation and monitor fields |

*A, Austria; B, Belgium; Fr, France; Fi, Finland; G, Germany; N, the Netherlands; S, Switzerland

In addition to data support systems from Table 4-2, most of the technologies and sensors from Table 4-1 are linked with individual data platforms. For example, Farm21, Agroplanning, MyJohnDeere, 365FarmNet, Dacom, Taakkaart, WIG, Agremo, AVR Connect or AFS Connect. While data sharing between different platforms is more and more feasible through API connections, not all platforms offer flexibility and user friendliness towards users. To facilitate data exchange, data standards concerning soil health are essential, for example, e-Lab, that is used by laboratories to exchange lab test results.

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