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Soil fertility in the EU taxonomy for the construction of new buildings

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Contents

Abstract

When soils are used for construction, all their ecosystem services are irreversibly lost. The European Commission has implemented various policies to reduce the loss of soils due to sealing, and this objective is integrated into the EU taxonomy for sustainable activities. In the delegated acts, specific criteria are defined to screen whether the building of new constructions can be considered environmentally sustainable. One of these criteria is that new constructions are not built on arable and crop land with a moderate to high level of soil fertility, and reference is made to the EU LUCAS survey with a hyperlink to the LUCAS project on the ESDAC website (https://esdac.jrc.ec.europa.eu/projects/lucas). Nevertheless, the data available in LUCAS soil do currently not provide a classification of soil fertility for the EU taxonomy regulation.

This report presents an overview of national legislations that classify agricultural land for spatial planning purposes, as well as EU and global methods and products (*i.e.* maps) to classify agricultural land. The advantages and disadvantages of these approaches as potential candidates for the EU taxonomy regulation criterion on soil fertility and new constructions are discussed. Considering recent developments in EU soil policies, the report proposes a new criterion for building new constructions on arable land that is better aligned with the European Commission's ambition of reaching no net land take by 2050.

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1 Introduction

1.1 Soil sealing and land take

Soil provides the foundation for buildings and infrastructure. However, when soil is used for construction, the provision of all its other key ecosystem services is irreversibly lost. Sealed soils lose their capability for providing food, biomass, fibres and raw materials; regulating water, carbon and nutrient cycles; and acting as a habitat for biodiversity. Between 2000 and 2018, the EU lost more than 700 km^2 of soil per year due to land take (EEA, 2019), which can be defined as the 'conversion of natural and semi-natural land into artificial land' (European Commission, 2023a). Possible consequences of land take and associated soil sealing are higher risks of flooding events (Pistocchi *et al.*, 2015), increased size of urban heat islands (Ward *et al.*, 2016), loss of a significant amount of carbon sequestration potential (Tóth *et al.*, 2022), and less food production capability in the EU (Tóth *et al.*, 2022).

1.2 The EU taxonomy regulation: soils for construction and real estate activities

The EU taxonomy is a classification system establishing a list of environmentally sustainable economic activities. It is meant to scale up sustainable investment in Europe and implement the European Green Deal. The EU taxonomy provides companies, investors and policymakers with criteria for determining which economic activities can be considered environmentally sustainable. In this way, it aims to create security for investors, protect private investors from greenwashing, help companies to become more climate-friendly, mitigate market fragmentation and help shift investments where they are most needed (European Commision, 2023).

The Taxonomy Regulation was published on 22 June 2020 and entered into force on 12 July 2020. It establishes the basis for the EU taxonomy by setting out four overarching conditions that an economic activity must meet to qualify as environmentally sustainable, related to the six environmental objectives, safeguards, and technical screening criteria. The Taxonomy Regulation empowered the Commission to adopt delegated and implementing acts afterwards, to specify how competent authorities and market participants shall comply with the obligations laid down in the directive. After the Regulation, four Delegated Acts have already been published and came into force: the Climate Delegated Act (2021, on sustainable activities for climate change mitigation and adaptation), the Disclosures Delegated Act (2021, on reporting), the Complementary Climate Delegated Act (2022, on nuclear and gas energy activities) and the Environmental Delegated Act (2023, on activities making substantial contribution to water, circular economy, pollution prevention and control and biodiversity and ecosystems).

The above-mentioned Climate Delegated Act and the Environmental Delegated Act contain criteria to define when the construction of new buildings can be considered as 'Taxonomy aligned' (i.e. environmentally sustainable according to the Taxonomy). In both cases, the delegated acts define Do No Significant Harm criteria of the construction of new buildings to the Protection and restoration of biodiversity and ecosystems. These criteria include the following requirements:

'New construction is not built on arable land and crop land with a moderate to high level of soil fertility and below ground biodiversity as referred to the EU LUCAS survey (ESDAC - European Commission, 2023)'

The reference to the EU LUCAS survey refers to the Land Use/Cover Area frame statistical survey Soil (LUCAS Soil), which is a topsoil survey that is carried out across the EU (Orgiazzi *et al.*, 2018). Surveys have been taken place in 2009/2012, 2015, 2018 and 2022. Topsoil samples were collected and analysed for a number of chemical, physical and biological soil properties (Ballabio, Panagos and Monatanarella, 2016; Ballabio *et al.*, 2019). Following the hyperlink that is provided in the taxonomy regulation, one finds an overview of the LUCAS topsoil datasets. However, the data available in LUCAS currently do not provide a method to classify soils according to soil fertility.

This criterion for the sustainable construction of new buildings as it is now, requires a classification method of EU agricultural land into high and moderate levels of soil fertility and biodiversity. The objective of this study is to provide an overview of national legislations that classify agricultural land for spatial planning purposes, and EU and global methodologies and products (i.e. maps) to classify agricultural land. The pros and cons of these approaches as candidates for the EU taxonomy regulation criterion on soil fertility and new constructions, are discussed. In addition, we will discuss the current criteria for the construction of new buildings as defined in the EU Taxonomy in the context of recent EU soil policies.

2 Methodology

2.1 National legislations with soil classification methods

We hypothesized that EU member states have methodologies in place that are part of existing legislation in relation to protect agricultural land from conversion to other land uses and sealing. Our aim was to assess which soil (and other) properties are part of the methodologies.

We therefore did a preliminary screening of national legislation in EU member states. The inventory was done based on the consultation of the Soil WIKI of DG ENV (EU login required, European Commission, 2020a), of scientific publications, or by contacting national administrations or researchers. The latter was done through a call through the European Environment Information and Observation Network of the European Environmental Agency, or through direct consultation of authors of relevant publications and research institutes. A summary of this inventory is given in Annex 1, and the list of contacted persons is given in Annex 2.

We want to stress that this was just a first preliminary screening and may not be complete. A project under the Soil Mission Work Programme 2023 may continue this work since one of the activities is to undertake a systematic review and analysis of how soils, their functions and ecosystem services as well as soil threats are considered in the various levels of spatial planning systems in EU and Associated Countries.

2.2 Review of methodologies to assess soil fertility and suitability at EU scale

The EU taxonomy stresses the importance of uniform criteria to which economic activities are evaluated (European Union, 2020). For example, recital 34 of the regulation on the establishment of a framework to facilitate sustainable investment, states that for each environmental objective, uniform criteria for determining whether economic activities contribute substantially to that objective should be laid down. The importance of uniform criteria hampers the use of national methodologies which are all different.

Therefore, we provide an overview of existing and applied methodologies that can be used at EU scale to classify agricultural land: the global agro-ecological zones (GAEZ), the Mars Crop Yield Forecasting System (MCYF) and a soil fertility index developed for Europe.

2.3 Soil suitability classification based on LUCAS topsoil data

In addition, we include an application of the GAEZ method using data from the Land Use and Coverage Area Frame Survey (LUCAS) 2009 topsoil database (Orgiazzi *et al.*, 2018) to test whether the LUCAS survey can be used for classifying agricultural land, as stated by the EU taxonomy. More information about the GAEZ method and the application using LUCAS topsoil data can be found in Annex 3.

3 Results

3.1 National legislations, guidelines and policies

Most member states have a methodology embedded in their legislation to classify agricultural land for spatial planning purposes. It must be noted that most of these methods have been developed more than 30 years ago, and often use relatively old data for applications.

Overall, we can differentiate three different methodologies that are used by member states:

- The classification of agricultural land based on agrochemical soil fertility (Czechia, Finland) embedded in legislation. It must be noted that most member states have methodologies to evaluate soil fertility, however, these are often not embedded in national legislations but rather in fertilizer recommendation guidelines (Higgins *et al.*, 2022). The evaluation of agrochemical soil fertility differs across member states in terms of soil properties, the analyses and the crops. These fertilizer recommendation guidelines were not included in this assessment.
- The classification of agricultural land based on land suitability, which includes indicators beyond (agrochemical) soil properties: Austria, Flanders, Wallonia, Bulgaria, Croatia, Czechia, Greece, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Slovenia, Estonia.
- The classification of agricultural land based on other indicators, such as monetary value (Hungary), and historical harvest data (Sweden).

Most of the methodologies applied by member states include physical, chemical, climate and terrain properties to evaluate the overall land suitability for agricultural production. The most common indicators used in land suitability assessments are physical soil properties (*e.g.,* texture, parent material, rockiness), soil type, climate and terrain conditions (*e.g.,* slope).

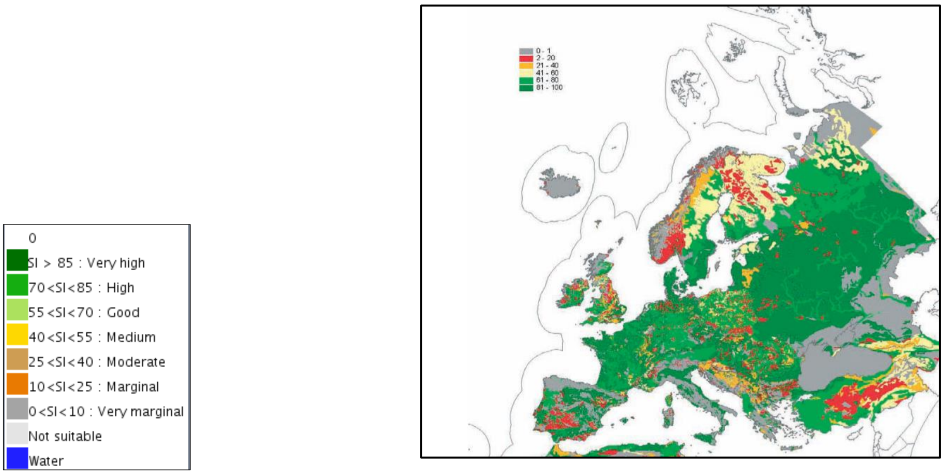
The context of these legislations and the purpose of the classification methods vary across member states. Most countries use the classification of agricultural land in the context of spatial planning in order to protect the most suitable agricultural land from other types of land uses, like the purpose of the EU taxonomy. Other member states use this classification for taxation of agricultural land, for land consolidation or for soil monitoring purposes.

3.2 EU-scale methodologies to assess soil fertility and land suitability

3.2.1 Mars Crop Yield Forecasting System

Soil data was integrated in the Crop Growth Monitoring System (CGMS) as part of the MARS Crop Yield Forecasting System (MCYFS) (Baruth, Genovese and Montanarella, 2003). Suitable soils were determined per crop group (root crops, cereals, and maize) on the basis of eight crop growth limiting properties of these soils: (1) slope, (2) texture (3) drainage, (4) rooting depth, (5) salinity, and (6) alkalinity, (7) stoniness, and (8) chemical toxicity. Each of the soil properties was derived as a qualitative variable in different classes, based on soil type and associated attributes with pedotransfer functions (Baruth, Genovese and Montanarella, 2003). No LUCAS data were used in this method. The result of this method for cereals is given in Figure 1.

Figure 1: Suitability map for cereals in Europe based on the Crop Growth Monitoring System (left). Suitability ranges from low to high suitability.

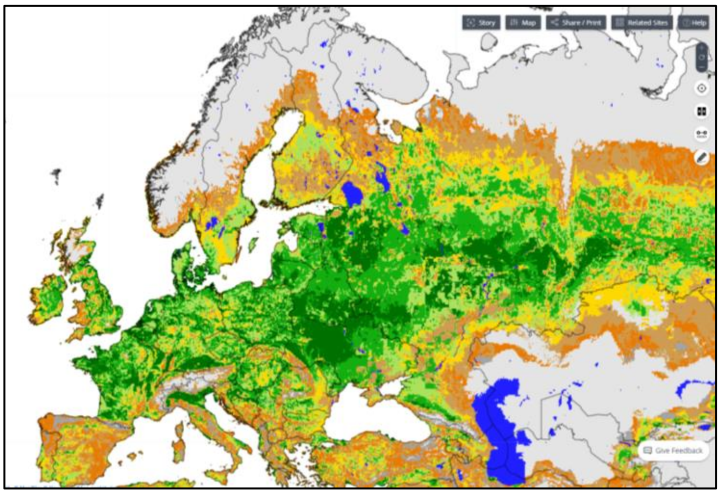


Source: Baruth et al., 2003. New soil information for the MARS Crop Yield Forecasting System.

3.2.2 The Agro-ecological zones approach

The Global Agro-Ecological Zones (GAEZ) approach, developed by the Food and Agricultural Organization of the United Nations (FAO), determines the cultivation potential of around 50 crops around the globe (Fischer et al., 2021). The assessment is based on the crop-specific analysis of climatic, soil, and terrain data. Figure 2 shows an extraction of the global suitability assessment for wheat based on climatic, soil and terrain data. For soils, the harmonized world soil database was used with soil types and related attributes, similarly as how it is used in the MCYFS.

Figure 2: The suitability based on the Agro-Ecological Zones approach developed by FAO, here shown for wheat production in Europe. The suitability index (SI) is calculated for wheat specifically based on climatic, soil and terrain conditions, ranging from very high suitability to not suitable.

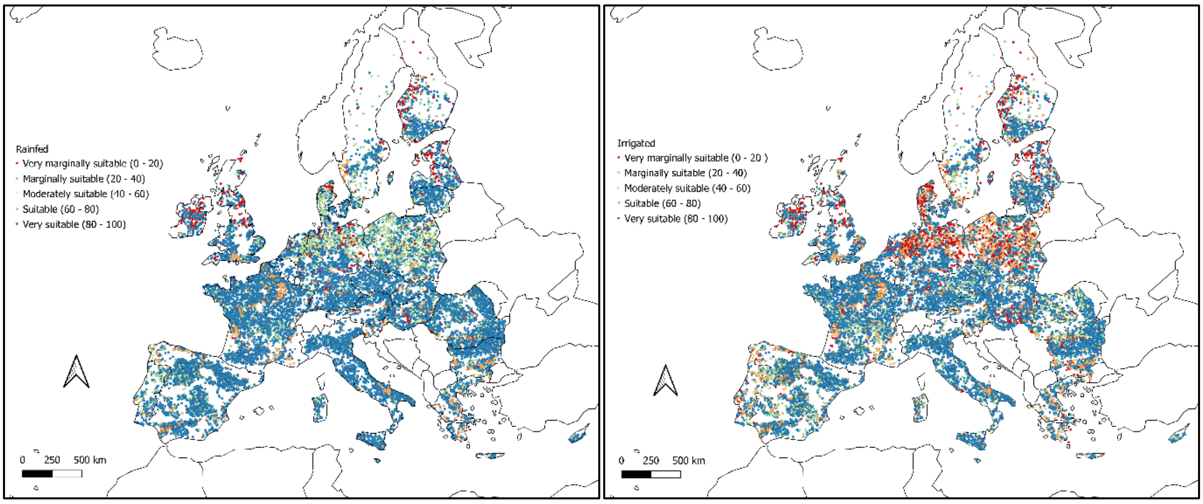


Source: Downloaded from the FAO GAEZ data portal on 26/04/2023

The soil suitability index represents seven soil functions or qualities: (1) nutrient availability, (2) nutrient retention capacity, (3) rooting conditions, (4) soil oxygen availability, (5) presence of lime and gypsum, (6) salinity and sodicity conditions, and (7) soil management and workability constraints. These seven functions are assessed based on various soil properties (*e.g.*, texture, organic carbon content, pH, exchangeable bases, cation exchange capacity, base saturation). The quantitative soil properties are classified into suitability classes, ranging from 'no constraint' to 'not suitable', using crop-specific threshold values. This classification can be based on linear relations (the higher or the lower, the better) or based on optimal relations (optimal pH, higher and lower values are sub-optimal). Qualitative soil properties (*e.g.* textural class, soil phase) are rated for each crop specifically. Terrain suitability is assessed based on the slope and location-specific rainfall characteristics in relation to soil erosion risks.

The data used to produce Figure 1 and 2 are coarse soil data based on general soil types. We used LUCAS 2009 topsoil data to assess soil suitability (excluding terrain and climate) for LUCAS grassland and cropland samples using the GAEZ method (Figure 3, Annex 3 for more information). Not all soil characteristics required by the GAEZ methodology (*e.g.* exchangeable bases) are available in LUCAS 2009 topsoil database, and these were not included in the assessment.

Figure 3: The soil suitability based on the Agro-Ecological Zones approach developed by FAO, using LUCAS 2009 topsoil data. The suitability index (SI) is calculated as the maximum score for a selection of crops based on available data from the LUCAS topsoil survey (see Annex 3).

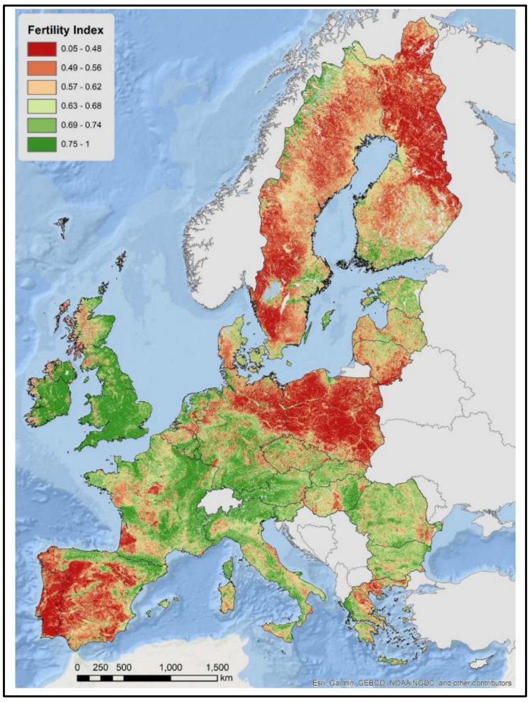


Source: Figure prepared for this report.

3.2.3 Soil fertility index

Panagos et al. (2020a) proposed a soil fertility index for Europe based on six soil properties: (1) soil organic carbon, (2) cation exchange capacity, (3) pH, (4) available phosphorus content, (4) exchangeable potassium content, (5) water-filled porosity, and (6) available water content. Each of these properties were given a score between 0 and 1, based on thresholds taken from literature and local experiments. The overall index was then calculated based on a weighted score of the six soil properties scores, for the whole of Europe (Figure 4). The outcome of this fertility index in soils is shown in Figure 4.

Figure 4: Soil fertility index calculated based on (1) soil organic carbon, (2) cation exchange capacity, (3) pH, (4) available soil phosphorus content, (4) exchangeable potassium content, (5) water-filled porosity, and (6) available water content.



Source: Panagos et al., 2022. Soil-related indicators to support agri-environmental policies

4 Discussion

4.1 Soil fertility is manageable and crop dependent

The Environmental Delegated Acts of the EU Taxonomy regulation set out criteria for the sustainable construction of new buildings (European Commission, 2023b). One of them is that new construction is not built on arable land and crop land with a moderate to high level of soil fertility. **Soil fertility is the ability of a soil to sustain plant growth by providing essential plant nutrients and favourable chemical, physical, and biological characteristics as a habitat for plant growth** (FAO, 2023b)**.**

It is important to note that **soil fertility can be maintained or increased** through several management practices, such as optimising soil nutrient management (FAO, 2023a). As a consequence, soil fertility is often evaluated in an agronomic context to define guidelines for agricultural management practices (Higgins *et al.*, 2022). The importance of soil management for soil fertility is also acknowledged in the recently proposed directive on soil monitoring and resilience or soil monitoring law (SML) (European Commission, 2023a): *'… Maintaining or increasing soil fertility over the long-term contributes to stable or even higher yields of crops…'*, and *'…The availability of healthy and fertile soils and land is crucial in the transition towards a sustainable bioeconomy and can therefore help increase and preserve the value of the land. Measures to increase soil fertility can also reduce farms' operational costs, such as the cost of inputs or machinery.'*

Given the fact that soil fertility is manageable, most classification systems embedded in national legislations of member states refer to land suitability rather than soil fertility. **Land suitability** or capability is the fitness of a given type of land for a defined use (FAO, 1976). For agricultural production, land suitability assessment includes not only the more inherent soil properties related to soil types, but also agro-climatic and terrain conditions. Land suitability often deals more with inherent landscape- and soil characteristics that are rather insensitive to management practices, such as slope and soil type.

In addition, soil fertility is crop dependent. For example, some crops grow well in acidic soils (Korcak, 1988), while others have an optimal pH above 6.5 (Hartemink and Barrow, 2023). This crop-dependency makes it very difficult, if not impossible, to establish uniform soil fertility criteria for all crops grown in the EU. This is also clear in Figure 4 when using a uniform soil fertility index across EU (Panagos and Borrelli, 2020b): large areas that are identified as soils with low fertility, are still important for agricultural production of particular crops (e.g. Poland).

4.2 Uniform criteria to assess soil suitability across Europe

The soil information for the crop growth monitoring system, as well as the GAEZ methodology, can be used as uniform criteria to assess soil suitability across EU of agricultural land. However, using one criterion based on coarse input data has the risk to classify whole regions as unsuitable or suitable, without having much variation within a region (Figure 1-3).

Figure 3 shows that the GAEZ method when using LUCAS topsoil data is capable of differentiating regionally (e.g. NUTS2) the suitability of soils for crop production. The GAEZ methodology was now applied on LUCAS point data, excluding criteria when LUCAS did not have the necessary input data. Future studies can improve the application of the GAEZ methodology by (1) using a combination of LUCAS topsoil data and pedotransfer functions based on soil types (Baruth, Genovese and Montanarella, 2003; Fischer et al., 2021) and (2) using the spatial interpretation of LUCAS topsoil data (Ballabio, Panagos and Monatanarella, 2016; Ballabio et al., 2019) as input to develop maps instead of point data.

It can be seen that some regions are still considered marginally or moderately suitable when using the GAEZ method, despite being important for agricultural production in the EU (e.g. Poland). It must be noted that some crops are not included in the GAEZ methodology that can be important locally. For example, apple production is highly important in Poland (EUROSTAT, 2023). However, this crop is not present in the GAEZ methodology. Therefore, when using this method, an evaluation of the existing tables in the GAEZ methodology should be updated for locally important crops.

4.3 The criteria of the taxonomy regulation in relation to other EU soil policies

The **Common Agricultural Policy (CAP)** foresees financial support for farmers that are farming areas facing natural or other specific constraints (ANCs), to prevent this land from being abandoned. These agricultural areas can be seen as less suitable for agricultural production due to inherent natural conditions. The natural constraints include eight climatic, soil, and terrain conditions: (1) low temperature, (2) dryness, (3) excess soil moisture, (4) limited soil drainage, (5) unfavourable soil texture and stoniness, (6) shallow rooting depths, (7) poor chemical properties, (8) steep slopes. These conditions used to assign ANCs are in line with the indicators used by the land suitability methodologies previously discussed, *i.e.* the GAEZ methodology and the CGMS methodology, and national methodologies used by most member states. Under the current CAP, the ANCs areas are defined by member states and the results can be found in their national strategic plans. For example, 39 % of the total agricultural area in Wallonia is constrained by natural conditions such as soil texture, limited drainage, limited rooting depth, and steep slopes (Wallonia, 2022). While the CAP promotes farming in these areas, the current criteria in the Environmental Delegated Act of the Taxonomy Regulation does not consider building on these areas as significantly harmful.

Since the publication and implementation of the EU taxonomy regulation in 2020, the European Commission has proposed new priorities, ambitions and regulations with great relevance to soil (Montanarella and Panagos, 2021), and soil sealing. In 2021, the European Commission published the **EU Soil Strategy** to reach all soils healthy by 2050 (European Commission, 2021). The strategy sets the ambition to reach **no net land take by 2050,** as sealed soils lose their capability of providing all soil ecosystem services and not only productivity. To do so, the strategy prescribes that Member States should integrate the **'land take hierarchy'** in Urban Greening Plans, and give priority to **reusing and recycling land and to quality urban soils** (European Commission, 2021). The land take hierarchy prescribes a hierarchy that needs to be applied in land planning: (1) **avoid** additional land take and sealing as much as possible; (2) if land take or sealing cannot be avoided, then it is better to **reuse** land that is already taken or sealed (e.g. demolishing buildings); (3) if it is not possible to avoid land take and sealing or to reuse land, then **impact should be minimized** and **mitigation and compensation measures** should be applied to minimize the loss of ecosystem services (e.g. infiltration and rainwater collection for water absorption) (European Commission, 2021). Given these recent policy developments, building on any agricultural land, irrespective of soil biodiversity and soil fertility level, goes against the ambition to achieve no net land take by 2050 of the European Commission (European Commission, 2020a, 2021). The current criterion in the EU taxonomy to define whether the construction of new buildings is sustainable, is also not the most sustainable practice according to the land take hierarchy as formulated in the Soil Strategy (European Commission, 2021). **Following the land take hierarchy, the new criterion could be that building new constructions shall not contribute to further land take and soil sealing.** This new criteria could be a simplification of the criterion not only in relation to soil fertility, as shown in Table 1.

Table 1: Current formulation in the EU taxonomy regulation (Annex 2, section 3) for the construction and real estate activities, and proposed new formulation

Current formulation	*Proposed new formulation*

The new construction is not built on one of the following: a) arable land and crop land with a moderate to high level of soil fertility and below ground biodiversity as referred to the EU LUCAS survey; b) greenfield land of recognised high biodiversity value and land that serves as habitat of endangered species (flora and fauna) listed on the European Red List[2] or the IUCN Red List[3]; c) land matching the definition of forest as set out in national law used in the national greenhouse gas inventory, or where not available, is in accordance with the FAO definition of forest[4].	The building of new constructions results in no net soil sealing.
[1] JRC ESDCA, LUCAS: Land Use and Coverage Area frame Survey (version of 27.6.2023: https://esdac.jrc.ec.europa.eu/projects/lucas). [2] IUCN, The IUCN European Red List of Threatened Species (version of 27.6.2023: https://www.iucn.org/regions/europe/our-work/ biodiversity-conservation/european-red-list-threatened-species). [3] IUCN, The IUCN Red List of Threatened Species (version of 27.6.2023: https://www.iucnredlist.org). [4] Land spanning more than 0,5 hectares with trees higher than five metres and a canopy cover of more than 10 %, or trees able to reach those thresholds in situ. It does not include land that is predominantly under agricultural or urban land use, FAO Global Resources Assessment 2020. Terms and definitions (version of 27.6.2023: http://www.fao.org/3/I8661EN/i8661en.pdf).	

Source: European Commission, 2023

The new formulation proposed in Table 1 requires verification of the net soil sealing induced by the constructor to check compliance. The proposed soil monitoring law requires Member States to monitor soil sealing using methods from scientific literature or publicly available (European Commission, 2023a). This monitoring framework will push the establishment of methods applied in practice to monitor net soil sealing. In addition, the European Environmental Agency uses a Copernicus product (10 m resolution) to monitor soil sealing (European Environmental Agency, 2021), which can be used to prove compliance at construction project level given the resolution.

The DNSH guidance for the Social Climate Fund, including a criterion to protect and restore biodiversity and ecosystems by new buildings, is currently under public consultation[1]. This criterion excludes forests, wetlands, peatlands, and permanent grasslands in Natura 2000 sites for the construction of new buildings, and encourages minimizing land take and soil sealing by recycling land, and mitigation measures. This criterion could also be an alternative formulation for the EU taxonomy regulation for the construction and real estate activities.

[1] https://climate.ec.europa.eu/document/download/197f1830-368f-4752-9aff-ff8623cf98fe_en?filename=policy_scf_dnsh_annex_1_buildings_en_0.pdf

5 Conclusions and recommendations

In the Climate and Environmental delegated acts of the EU Taxonomy Regulation, criteria are defined to classify the building of new constructions as environmentally sustainable. One of these criteria is that new construction is not built on arable and crop land with a moderate to high level of soil fertility, and reference is made to the EU LUCAS survey with a hyperlink to the LUCAS project on the ESDAC website (https://esdac.jrc.ec.europa.eu/projects/lucas). The data available in LUCAS soil do currently not provide a classification of soil fertility for the EU taxonomy regulation.

We found that most Member States have a legislation to protect agricultural land from land use conversion that includes a classification system to value agricultural land. Most member states do assess **land suitability rather than soil fertility,** that goes beyond manageable agrochemical soil properties (texture, parent material, rockiness, soil type, climate and terrain conditions (e.g., slope)).

The EU taxonomy stresses the importance of uniform criteria to which economic activities are evaluated (European Union, 2020), hampering the use of national methodologies which are all different. We have shown the results of three methodologies applied across the EU to define land suitability and soil fertility for agricultural production. These methodologies apply **uniform criteria**, these methods can be used to classify **land based on actual measurements** by the constructor, or **the resulting maps can be used to assess the fertility or suitability of an area**. The challenge of using these methodologies and maps is that they are **crop dependent** and **do not cover all crops** present in the EU that can be important regionally. The **resulting maps are rather coarse** due to coarse input data. **Future research** may however improve the maps, by substituting part of the inputs with LUCAS topsoil data.

Soil sealing on *any* land results in the loss of all the soil key ecosystem services that go far beyond biomass production alone (European Commission, 2021). Building on *any* agricultural land (even with low fertility) therefore goes against the ambition to achieve no net land take by 2050 of the European Commission (European Commission, 2021, 2020), and does not follow the land take hierarchy formulated in the Soil Strategy. The latter gives priority **to reusing and recycling land that is already sealed or taken, and when soils are sealed compensation should be done.** When reformulating the DNSH criteria for the EU taxonomy, the land take hierarchy can be used to screen whether the building of new constructions are sustainable.

6 Further research

We do note that the inventory of national legislations in this report gives a preliminary screening on how soils are used in spatial planning of rural and agricultural areas. A project under the Soil Mission Work Programme 2023 (HORIZON-MISS-2023-SOIL-01-06, call closed on 20 September 2023) will continue this work since one of the activities is to undertake a systematic review and analysis of how soils, their functions and ecosystem services as well as soil threats are considered in the various levels of spatial planning systems in EU and Associated Countries. Future calls under the Soil Mission 2024 program may address land suitability or soil fertility in relation to sustainable soil use as aimed by the EU soil taxonomy. In addition, soil fertility is often evaluated in an agronomic context based on soil analyses, management practices and crop types. However, these guidelines are often not embedded in legislation but drive farming practices in the EU based on soil analyses. A complete overview of these guidelines and the different methodologies used for soil analyses is currently missing.

Current national methods and accompanying data to assess land suitability, are often old and outdated. Chemical soil fertility properties are often completely excluded in these methods, while a combination of inherent and fertility soil parameters may be informative on suitability and fertility (*e.g.*, past investments and management practices). One example of such a combined system is the national land productivity assessment of Lithuania (see Annex 1), where the suitability score of a parcel is calculated based on inherent soil properties (texture, parent material and drainage class, stoniness, climatic conditions) and on agrochemical soil fertility (soil phosphate and potassium content, soil organic carbon content). Finally, current national and European systems assess land suitability based on productivity. However, yield alone may not be enough to measure land suitability for agricultural production in the EU (Hack-ten Broeke *et al.*, 2019). In modern agriculture, inputs such as fertilizers, irrigation and crop protection products, make it possible to make almost all soils suitable for agriculture. In that sense, **a more appropriate definition of suitable soils are those soils that have maximal yields with minimal use of inputs and minimal environmental pressures** (Hack-Ten Broeke *et al.*, 2008). In such a framework, not only yield but also nutrient use efficiency, nitrogen leaching, water use efficiency, soil carbon sequestration potential, among others, could be included to assess land suitability. However, methodologies that take into account other parameters except yield are not yet widespread among member states nor at European level (Hack-ten Broeke *et al.*, 2019). More research and development is therefore needed, which can be accomplished by the Soil Mission program.

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List of abbreviations and definitions

SML	Soil Monitoring Law
DG ENV	Directorate-General Environment
GAEZ	Global Agro-ecological Zones
FAO	Food and Agricultural Organization of the United Nations
SI	Suitability Index
CGMS	Crop Growth Monitoring System
MCYFS	Mars Crop Yield Forecasting System
CAP	Common Agricultural Policy
ANC	Areas facing natural or other specific constraints

List of figures

List of tables

Annexes

Annex 1. An overview of national legislation and guidelines to classify agricultural land in high to moderate fertility or suitability.

Table 1: National legislation and guidelines

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
AUSTRIA	AT	Evaluation of soil fertility based on Soil Taxation Survey at 1 m depth. Soil units (=homogeneous areas with same productivity potential are defined based on soil type (soil textural triangle), soil condition stage, parent material if cropland (alluvium, diluvium, loess, weathering, ...), climatic and water stage if grassland. This soil estimation is the basis for the yield estimate. 5 states (Upper Austria, Salzburg, Tyrol and Carinthia, Styria) are using soil functions (among which soil fertility is 1 one) for their spatial planning.	Physical, climate	Taxation Protection of agricultural land in spatial planning	Bodenschätzungsgesetz 1970, BGBl. No 233/1970	https://dafne.at/content/report_release/aa85879d-af0f-4273-a1e2-b7f1d7178d41_0.pdf	https://esdac.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/esb_rr/n06_soilresources_of_europe/PDF/AUST05.pdf https://www.land-oberoesterreich.gv.at/106895.htm https://www.bmf.gv.at/themen/steuern/immobilien-grundstuecke/grundbesitzabgaben-einheitsbewertung/land-und-forstwirtschaftliches-vermoegen-bodenschaetzung.html http://dx.doi.org/10.1016/j.geoderma.2015.09.023 https://www.regioplan.org/5mf/prj/rp/pdf/upload/3_11_ZBOS_Sutor_V03.pdf
BELGIUM	BE FL	Ruimtelijk structuurplan Vlaanderen (RSV) aims to increase natural and forest areas with 38 000 and 10 000 ha respectively due to conversion of agricultural land. When converting agricultural land, land is selected that is less suitable for agriculture (erosion, flooding), together with the actual use and the importance of this land for agricultural farms. Soil suitability maps are consulted during this process. These suitability maps are based on texture, drainage class, soil development (horizons), parent material, profile development and fase of development, artificial soils. The delineation of the agrarian structure of the landscape is very much driven by the physical structure of the landscape (e.g. rivers, ...)	Physical	Protection of agricultural land in spatial planning	Afbakening van de gebieden van de natuurlijke en agrarische structuur (AGNAS) binnen Ruimtelijke Structuurplan Vlaanderen, decreet 1997.	https://www.milieuinfo.be/dms/d/d/workspace/SpacesStore/192c60bd-c230-4fd4-abbe-90ab7697cdec/Toelichting%20landbouweconomische%20bodemgeschiktheid.pdf	RSV2011 (2)_0.pdf (vlaanderen.be)
	BE WA	- Although the CoDT legislation specifies the need to protect soil quality in land use planning, it does not give a clear definition about soil quality (soilver report) - In article D.281 of the agricultural code, soil quality must be taken into account when an exchange of parcels must be done within a land consolidation perimeter. The cropping value (points) is based on oxidation/reduction spots, the presence of an indurated horizon or a shallow substrate, stoniness, texture, soil map, other characteristics like water stagnation, ... The contextual value represent degrading factors for agricultural exploitation such as slope and hedge border effect. The analysis is done by experts on the field and based on soil maps.	Physical, chemical	Land consolidation	Agricultural code (M.B. 05.06.2014 - en vigueur le 15.06.2014 sauf exceptions) ; Code du Développement Territorial (CoDT)	https://www.gissol.fr/presentations/IGCS2011session3_Classement_terres_Wallonie_Henquin.pdf	https://www.soilver.eu/wp-content/uploads/2022/02/SOILveR_SOILVAL-Synthesis_end-of-project_final_ENG.pdf

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
BULGARIA	BG	The change of the designation of agricultural lands for non-agricultural needs shall be allowed depending on the productive qualities of the land and the objectives of the change. Land is classified is done based on 7 indicators: clay content, depth of the organic horizon, depth of soil profile, textural coefficient, SOM content in upper layer, pH, soil water level. These scores are related with yields, ranging from 1 (lowest yields) and 100 (highest yields). If one indicator scores 0, the overall score is also 0. The soil fertility evaluation is calculated as a land evaluation score, by correcting it for soil erosion or accumulation, soil salinity/alkalinity, rockiness, swamping, climate. The average land evaluation value is the average of the land evaluation of 10 selected among 18 agricultural crops (with more importance to winter wheat since that one is most important in BG).	Physical, chemical, erosion, rockiness, climate, swamping	Protection of agricultural land in spatial planning	Agricultural Land Protection Act	https://doi.org/10.7494/geom.2020.14.3.89	
CROATIA	HR	Quality of land is a score based on soil (development/depth/stones, texture and parent material), climate (zone) and relief (slope, flooding, exposure), shape and size of the parcel. There are 4 classes: particularly valuable, valuable, other arable land, other agricultural land. Particularly valuable and valuable land may not be used for non-agricultural purposes (with some exceptions).	Physical, climate, relief, shape and size parcel	Protection of agricultural land in spatial planning	Law on Agricultural Land ORDINANCE ON CRITERIA FOR DETERMINING PARTICULARLY VALUABLE ARABLE (P1) AND VALUABLE ARABLE (P2) AGRICULTURAL LAND	https://narodne-novine.nn.hr/clanci/sluzbeni/2019_03_23_470.html	
CYPRUS	CY	We did not find any methodology to classify agricultural land in Cyprus.	/	/	/	/	/
CZECHIA	CZ	1. Soil fertility of agricultural soils: P, K, Mg measured in Mehlich-3 and pH, optimal values are defined by law; 2. Agricultural land is divided according to its quality into 5 classes of agricultural land protection. Agricultural land of poorer quality shall be withdrawn as a priority, agricultural land of protection class I and II may be withdrawn only in cases where another public interest significantly outweighs the public interest in the protection of the agricultural land fund. Classes are made based on the land ecological units (BPEJ), which exists out of 5 digits or factors: climate region, soil type, slope, exposure, skeleletality and soil depth	1. Chemical soil properties 2. Climate, soil type, slope, skeletality, soil depth, exposure	Agrochemical testing of agricultural soils Protection of agricultural land in spatial planning	1. Decree of the Ministry of Agriculture No. 275/1998 Coll., on agrochemical testing of agricultural soils and determination of soil properties of forest land 2. Act No. 334/1992 Coll. Act of the Czech National Council on the Protection of Agricultural Land Fund Decree 48/2011 Coll. (vyhláška o stanovení tříd ochrany) Decree on the establishment of classes of protection Decree No. 327/1998 Coll. Decree of the Ministry of Agriculture, laying down the characteristics of credited soil ecological units and the procedure for their management and updating	https://www.zakonyprolidi.cz/cs/1998-327 https://www.zakonyprolidi.cz/cs/2011-48	

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
DENMARK	DK	Municipalities spatial plans need to contain guidelines for the safeguarding of agricultural interests, including the designation and safeguarding of particularly valuable agricultural areas. The method for selecting these particularly valuable agricultural areas is not established at federal level, but needs to be decided by the municipalities. Some examples are given in the references.	Can vary across municipalities	Protection of agricultural land in spatial planning	The planning act	https://kommuneplan2021.odder.dk/land-og-vand/landbrug/vaerdifulde-landbrugsomraader/ https://kommuneplan2021.horsens.dk/retningslinjer/erhverv-landbrug/saerligt-vaerdifulde-landbrugsomraader/ https://kommuneplan.norddjurs.dk/temaer/erhverv/jordbrug/saerligt-vaerdifulde-landbrugsomraader/	
ESTONIA	EE	The planning act defines that the county-wide spatial plans are to state the general conditions of use for the preservation of valuable agricultural land, landscapes and natural biotic communities; the Comprehensive plans should designate valuable agricultural land and to state the conditions for their protection and use. There are no general rules institutionalized by law to determine the valuable agricultural land. Current recommendations by the ministry of rural affairs is that valuable land consist of areas larger than two hectares and with weighted average productivity grade of soil equal or higher than 41 points (which is the national average value) or the average productivity value of the county if that is lower than the national average value. The productivity grade is based on soil type, soil organic carbon content, hydrological conditions, slope, etc.	Physical, chemical, terrain	Protection of agricultural land in spatial planning	Planning Act	https://llufb.llu.lv/conference/economic_science_rural/2014/ESRD_36_2014_Integrated_Sustainable.pdf	https://www.riigiteataja.ee/en/eli/ee/Riigikogu/act/522122015001/consolide;
FINLAND	FI	Based on soil pH-H2O, Ca-AAAc, PO4-AAAc, K-AAAc, Mg-AAAc, Mg:Ca, Mg:K, Na-AAAcEDTA, B-HotWater, Cu-AAAcEDTA, Mn-AAAcEDTA, Zn-AAAcEDTA, Mo-AAAcEDTA, agricultural soils are classified into 6 fertility classes.	Chemical	Agrochemical testing of agricultural soils	/	https://cdnmedia.eurofins.com/european-east/media/2857469/eurofinsagro_viljavuustutkimuksentulkinta_06022020_teroprint.pdf	

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
FRANCE	FR	Agricultural areas whose preservation is of general interest either because of the quality of their production, or their geographical location, or their agronomic quality may be classified as protected agricultural areas. These are delimited by prefectoral decree taken on the proposal or after agreement of the municipal council of the interested municipalities or, if necessary, and after opinion of the municipal council of the interested municipalities, on the proposal of the deliberating body of the public establishment competent in the matter of the local urban plan or the territorial coherence scheme, after the opinion of the chamber of agriculture, of the National Institute of Origin and Quality in the areas of controlled designation of origin and of the departmental commission for the orientation of agriculture and after a public inquiry carried out under the conditions provided for in Chapter III of Title II of Book I of the Environment Code. The existence of small wooded parcels within such a zone is not an obstacle to this delimitation.	Can vary across municipalities	Protection of agricultural land in spatial planning	Code rural et de la pêche maritime	Section 1 : L'affectation de l'espace agricole et forestier (Articles L112-1 à L112-3) - Légifrance (legifrance.gouv.fr)	https://doi.org/10.1016/j.landusepol.2019.104031
GERMANY	DE	The soil estimate is used to determine the natural productivity of the arable land for the valuation of agricultural assets. In addition to determining the assessment basis for various taxes (about 20 tax applications, e.g. Property tax, income tax), their results also serve various non-tax purposes (e.g. to determine the value of land consolidation procedures). Classification is done differently for grassland and arable land, based on soil type (texture), climate, hydrological features, parent material (alluvial, dilluvial, wind, weathering), different classes based on soil depth, signs of acidity and water regime, depth, biological activity, …	Physical, chemical, biological, climate	Taxation Land consolidation	Bodenschätzungsgesetz – BodSchätzG) of 20 December 2007 (BGBl. I pp. 3150, 3176) within the framework of the Annual Tax Act 2008.	https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Steuern/Weitere_Steuerthemen/2014-07-21-bodenschaetzung.html; https://via.bund.de/bmf/muster/map/https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Steuern/Weitere_Steuerthemen/2014-07-21-bodenschaetzung-anlage-VRBodSchaetzG.pdf?__blob=publicationFile&v=2	
GREECE	EL	Land is classified into classes done based on 8 criteria: drainage, texture, soil depth, pH, stoneniness, electrical conductivity, slope, CaCO3	Physical, chemical, terrain	?	Joint Ministerial Decision 168040/2010	http://www.minagric.gr/images/stories/docs/agrotis/XOROTAJIA/kya168040_2010.pdf	

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
HUNGARY	HU	Change of land use of quality land higher than the average is more restricted, and procedures are more complicated; land of average quality: the municipality in question, including the metropolitan district and the Inytv, as defined in Act CXLI of 1997 on the Land Register (hereinafter referred to as the Inytv.). In the case of the towns referred to in Paragraph 10(1), the district shall be divided into: - land corresponding to the area-weighted average of the golden crown values per 1 hectare of its agricultural lands of the same type of cultivation; "	Monetary value	Protection of agricultural land in spatial planning	Act CXXIX of 2007 on the protection of land	https://net.jogtar.hu/jogszabaly?docid=A0700129.TV	
IRELAND	IE	The National Landscape Strategy recognises the importance of landscape protection and its interconnectivity with biodiversity and climate change. It also recognises that Ireland's soils and geology are a key component in defining and forming our landscape. One of the outputs is a data framework on a national GIS platform to provide the structure for on-going collection, monitoring and review of the landscape's physical - including soils and water catchment - scientific, ecological, biodiversity and cultural data. It will reflect existing environmental classifications and national and local initiatives on land-cover and land-use habitat mapping. This output may be useful for spatial assessment of land productivity and soil fertility.	Unknown	Protection of agricultural land in spatial planning	NATIONAL LANDSCAPE STRATEGY	https://www.gov.ie/pdf/?file=https://assets.gov.ie/95852/388d4758-50c1-42bd-9adc-0bdfe1291765.pdf#page=null	
ITALY	IT	Priority areas for agricultural land use at the regional level; for example the South Milan Agricultural Park. Manual of Methods for Soil and Land Evaluation was published in 2009, land capability classification based on physical (rooting depth, available water capacity, texture, stoniness, drainage class), chemical (chemical fertility, salinity), erosion, terrain (flooding risk, drainage), slope, climate	Can vary across regions Manual based on physical, terrain, chemical and climatic properties and erosion	Protection of agricultural land in spatial planning	https://www.unirc.it/documentazione/materiale_didattico/598_2009_214_6447.pdf		https://doi.org/10.1016/j.landusepol.2019.104031

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
LATVIA	LV	Low quality land is given priority for changing agricultural land to forest land; If the quality > 50 points there may be restrictions on land subdivision and changing land use; Mapping soil and quality shall be carried out for agricultural land at least every 20 years, last assessment dates from 25 years ago and shall be done again 1 January 2028.	Unknown	Taxation Protection of agricultural land in spatial planning	Law management law Regulations Regarding Mass Appraisal (cadastral value)	/	
LITHUANIA	LT	Nb = Bnb × K1 × K2 × K3 × K4 × K5 × K6. with BnB = a score based on the soil textural class and parent material and drainage class with K1 correction factor based on soil pH with K2 correction factor based on soil phosphate concentration with k3 correction factor based on soil potassium and soil organic carbon content with K4 correction factor based on stoniness with K5 correction factor based on the variability of soil types within the parcel with K6 correction factor based on climatic conditions	Physical, chemical, climate	?		https://www.e-tar.lt/portal/lt/legalAct/TAR.C5296083B1BF	
LUXEMBOURG	LU	Soil fertility is not taken into account in spatial planning; New policy strategy on the way with 'no net land take' goal by 2050. Interesting ongoing project named Agricultural and Horticultural Suitability Map of Luxembourg (AHSL) which will produce 4 suitability maps for cropland, grassland, vegetable and fruits.	AHSL: climate, physical, erosion, water use, topography, validated based on satelite data to estimate productivity	/		https://liser.elsevierpure.com/en/projects/agricultural-and-horticultural-suitability-map-of-luxembourg	

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
MALTA	MT	The rural policy and design guidance document (2020) states that it aims to ensure proper conservation and management of rural areas for both present and future generations by ensuring the sustainable use of rural resources, and by Avoiding unnecessary urbanisation of the countryside and loss of rural land to built structures and urban-type interventions; and by nsuring the overall protection and preservation of rural areas and curbing activities that lead to degradation or deterioration of rural resources whether through soil erosion, soil sealing, land impermeabilization, flooding, pollution and illegal dumping of waste, or otherwise. We did not find a specific methodology to value agricultural areas.	/	/	/	https://meae.gov.mt/en/Public_Consultations/MECP/PublishingImages/Pages/Consultations/ReviewoftheRuralPolicyDesignGuidancePhase2/RURAL%20POLICY%20AND%20DESIGN%20GUIDANCE%202020.pdf	
NETHERLANDS	NL	There used to be a legislation (Wet Inrichting Landelijk Gebied) in which soil suitability was taken into account in the context of land consolidation. However, the legislation is not in force anymore, and there was never a national methodology (only at regional scale). Report of 2007 investigated whether it is feasible and valuable to classify soils for agricultural use in the Netherlands. However, the definition was not limited to natural productivity or fertility, but the aim was to assess which soils lead to highest yields with minimal pressure on the environment and minimal use of external inputs. Results have been translated for Northern Brabant province, in which the soil suitability is based on the highest productivity given changing hydrological conditions.	Environmental pressures	/	/	https://edepot.wur.nl/576638	https://edepot.wur.nl/576638 https://edepot.wur.nl/42722 https://doi.org/10.1016/j.geoderma.2018.11.002
POLAND	PL	Change of land use is restricted on high quality soils. The soils are classified into 6 classes; depending on mineral and organic soils and the position (e.g. Lowland).	Qualitative evaluation of soil type, water relations, water and drainage structures, elevation, terrain	Protection of agricultural land in spatial planning	Law of 3 February 1995 on the protection of agricultural and forest land; REGULATION COUNCIL OF MINISTERS of September 12, 2012 on soil classification of land	https://sip.lex.pl/akty-prawne/dzu-dziennik-ustaw/ochrona-gruntow-rolnych-i-lesnych-16796586?unitId=art(10); https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20120001246/O/D20121246.pdf	

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
PORTUGAL	PT	The RAN national agricultural reserve) is the set of areas that in agro-climatic, geomorphologic and pedologic terms have greater aptitude for agricultural activity; Land is classified either based on the LAND APTITUDE CLASSIFICATION METHODOLOGY by FAO (A1 - A4; A0) or by the methodology defined by the former National Center for Agrarian Recognition and Planning (CNROA) (A, B, C, Ch, D, E). RAN=A1, A2, A, B, Ch, alluvial and colluvial lowlands	Soil thickness, stoniness, slope, erosion risk, rocky outcrops, fertility, toxicity, soil water availability	Protection of agricultural land in spatial planning	National Agricultural Reserve	https://dre.pt/dre/detalhe/decreto-lei/73-2009-603209	
ROMANIA	RO	The soil fertility is divided into 5 classes using bonitation scores based on climatic properties (rainfall, temperature), chemical properties (salinization/alkalinization, gleyic properties, pollution, CaCO3 content, base saturation, humus layer thickness), physical properties (texture, porosity), landscape properties (slope, landslides, groundwater depth, floodability, excess moisture at surface)	Climate, physical, chemical, terrain	General assessment of soil quality Protection of agricultural land in spatial planning Fertilizer recommendations Soil remediation needs Subsidies from the rural development fund	An integral part of Order 212/2002, Order 145/2002: PART I SUBSIDISATION OF AGRICULTURAL LAND AND ITS CLASSIFICATION IN QUALITY CLASSES | Technical regulation	https://lege5.ro/Gratuit/gqytamru/partea-i-bonitarea-terenurilor-agricole-si-incadrarea-in-clase-de-calitate-a-acestora-norma-tehnica?dp=gizdknbwgyzdq	
SLOVAKIA	SK	Bonitation soil-ecological units = 7 digits code that includes: climatic region, soil type, slope, exposure, gravel content, depth and texture. They are spatial locations with same production parameter. PV = (ST + SE + GD + ST). TP where: PV = point value of the Bonitation soil units, ST = point value of soil type (interval 1-60 points), SE = point value of slopes and exposure of the landscape (interval 1-15 points), GD = point value of gravel contents in the soil and soil depth (interval 1-15 points), ST = point value of soil texture (interval 1-10 points), TP = coefficient of the climatic region (interval 1.00-0.59). Based on PV, land is classified into 9 quality grades.	Physical, chemical, climate, terrain	Protection of agricultural land in spatial planning	Legislation Act No. 220/2004 Concerning the Protection and Use of Agricultural Soil (Soil Protection Act). The Soil Protection Act is supplemented by the Government Order No. 58/2013 which has provisions to protect high-quality soils and prescribes a financial levy for land take.	https://www.zakonypreludi.sk/zz/2013-58	https://doi.org/10.1080/17445647.2018.1428233

Country Name	Country code	Type of tool	Indicators	Why	References to legislation	References to methodology	Other references
SLOVENIA	SI	The proposal for areas of permanently protected agricultural land shall include land which has a land rating in accordance with the regulations governing the registration of immovable property hereinafter referred to as "rating") of more than 35. For the purpose of determining the proposal for areas of permanently protected agricultural land, land shall be classified in classes with a rating:(a) 0 to 35; b) 36 to 50;(c) 51 to 60; and (c) 61 to 100. The score is based on soil (texture; soil skeleton, soil type and development stage), climate (precipitation and temperature), slope, rockiness, flooding, dryness, exposure, openness, shading	Physical, climate, terrain	Protection of agricultural land in spatial planning	Agricultural land act Rules on the determination and management of land credit rating (Official Gazette of the Republic of Slovenia, No. 47/08, 54/21 – ZKN and 41/22)	http://www.pisrs.si/Pis.web/pregledPredpisa?id=PRAV12299	
SPAIN	ES	Some regulations for cropland protection at the regional and municipal levels.	Can vary across municipalities	-	-	-	https://doi.org/10.1016/j.landusepol.2019.104031
SWEDEN	SE	A classification system of Swedish arable land was developed in 1971 based on harvests in 1969. The land was classified on a scale from 1 to 10, where 10 indicated the highest agricultural production capacity and 1 indicated nearly no production capacity. The classification of the land is based solely on parameters related to production, i.e., the sizes and monetary values of harvests in that particular period. (Royal Board of Agriculture, 1971). These maps were based on the type of production and yields of that time, but they are reported to still be in use to some extent in current spatial-planning processes in Sweden, The Swedish Board of Agriculture (2018b), however, concludes that the classification system is obsolete and should be replaced with a new model for valuing agricultural land, where several different types of values are incorporated, e.g., food production, biodiversity, ecosystem services, climate adaptation and food contingency planning issues (Environmental Objectives Council, 2019).	Monetary value	Protection of agricultural land in spatial planning	The Swedish Environmental Code	/	https://publications.slu.se/?file=publ/show&id=111796 https://jordbruketisiffror.files.wordpress.com/2013/10/akerklassificering_19710211.pdf https://doi.org/10.1016/j.landusepol.2020.104714

Annex 2. List of contact persons

Table 2: Name and affiliation of contact persons

Country Name	Country code	Name	Affiliation
AUSTRIA	AT	Andreas Knoll	REGIOPLAN INGENIEURE
		Huber Sigbert	Umweltbundesamt GmbH
BELGIUM	BE	Esther Goidts	Service Public de Wallonie - Agriculture, Ressources naturelles et Environnement Département du Sol et des Déchets
		Christophe Vandevoort	Projectleider AGNAS Vlaanderen
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Annex 3. GAEZ

GAEZ methodology

Module IV of the GAEZ methodology estimates yield reductions due to soil and terrain-slope constraints. To assess soil-suitability, seven soil qualities (SQ) are defined consisting each time of soil indicators which are rated. Soil characteristics suitability ratings can be not suitable (10), Very severe constraint (30), Severe constraint (50), Moderate (70), Slight constraint (90) and No constraint (100).

Excel tables exist that give ratings for each soil characteristic (Table 1) depending on crop type (56 rainfed and 45 irrigated crops), input level (high, intermediate and low) and water supply system (rain-fed, gravitiy irrigation, sprinkler irrigation and drip irrigation).

After the ratings are collected for each individual soil characteristic, overall ratings are calculated for each soil quality. For some qualities, a differentiation is made between topsoil (0-30 cm) and subsoil (30-100 cm). The overall rating for some of the soil qualities (SQ1, SQ2 and SQ7) is calculated as the average between the lowest rating and the average of the remaining ones:

$$SQ = f_{SQ}(x_1, \dots, x_m) = \frac{\tau(x_{jo}) + \frac{1}{m-1}\sum x_j}{2} \qquad \text{Eq. 1}$$

For others, the minimum is used (SQ4, SQ5 and SQ6) or the value for a specific characteristic multiplied by the minimum of the others (SQ3). When different soil depths are considered, a weighing factor depending on the crop root system is used.

The overall soil suitability is calculated as follows:

$$SR = 0.5 * (SQ1 + SQ2) * SQ3 * fSR(SQ4, SQ5, SQ6, SQ7) \qquad \text{Eq. 2}$$

with fSR calculated as Eq. 1.

Although equation 2 is used for intermediate input farming and not for high input farming, which is probably most relevant for European agricultural systems, we opted to use this equation as it includes all soil qualities.

To assess terrain suitability, tables have been developed that represent yield reductions depending on slope type per crop group. The effect of slope on land suitability depends on the rainfall amount and distribution, which is in the GAEZ methodology assessed as the ratio of 12 times the sum of the squared monthly precipitation, divided by the sum of the monthly precipitation.

GAEZ application using LUCAS 2009 topsoil database

We used LUCAS 2009 topsoil database to calculate for each soil sample, taken in either grassland or cropland, the soil suitability for a selection of crops (wheat, rice, maize, barley, rye, oat, potato, sugar beet, phaseolus beans, chickpea, sunflower, olive, tomato, citrus, grass and carrot). The overall suitability was then calculated as the maximal score out of the score for each of the crops. To be able to use LUCAS topsoil database, we had to make some simplifications:

(1) Suitability for the soil quality 4 and 5 (oxygen availability and presence of lime and gypsum) was not calculated and left out of the overall suitability, as these data are not available in LUCAS topsoil database

(2) As subsoil data are not available in LUCAS 2009 topsoil database, this was not included in the overall assessment.

(3) Not all soil characteristics required by the GAEZ methodology (*e.g.* exchangeable bases) are available in LUCAS 2009 topsoil database, and these were not included in the assessment. We used soil pH, texture, soil organic carbon, pH, CEC, coarse fragments, lime content, and soil type (for vertic and gelic properties) in the assessment.

Table 3: List of soil characteristics that are rated in the GAEZ method to assess the overall rating of soil qualities and soil suitability.

	SQ1 Nutrient availability	SQ2 Nutrient retention capacity	SQ3 Rooting conditions	SQ4 Oxygen availability	SQ5 Presence of salinity and sodicity	SQ6 Presence of lime and gypsum	SQ7 Workability
Texture	X	X					X
Clay		X					
Soil Organic Carbon	X						
pH	X						
Total Exchangeable bases	X						
Base saturation		X					
Cation Exchange Capacity		X					
Soil Depth			X				X
Soil Phase			X	X		X	X
Soil property rating			X				
Soil depth/volume			X				
Drainage				X			
Exchangeable sodium percentage					X		
Electrical conductivity					X		
Calcium Carbonate						X	
Gypsum						X	
Soil Gravel Content							X
Vertic properties							X

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