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Unveiling the Soil beyond Definitions: A Holistic Framework for Sub-Regional Soil Quality Assessment and Spatial Planning

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Abstract: The issue of land/soil consumption and degradation has been extensively explored in international literature, yet a universally accepted definition of soil quality remains elusive. Over the decades, the scientific community has witnessed the evolution of the concept of land/soil quality, with varying nuances across different disciplines. The absence of a shared definition poses challenges in addressing local concerns and preserving the distinctiveness and well-being of the soil. The present paper seeks to fill this gap from the spatial planning perspective by proposing a soil quality detection framework tailored for the sub-regional spatial context, offering support in particular for local planning decisions. The concept of soil quality is approached comprehensively, and the indicators put forth are selected based on specific soil functions, services, or threats. To support this all-encompassing approach through a case study in the Italian context, this paper suggests integrating 11 datasets and 55 indicators. This extensive dataset aims to quantify and generate meaningful cartographic representations, offering a multifaceted and detailed understanding of soil quality within the sub-regional context. The goal is to establish a framework that facilitates a more holistic understanding of soil quality, aiding in effective spatial planning and policy-making processes.

Keywords: land planning; rural planning; supra-local planning; ecosystem quality

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1. Introduction

1.1. Soil Quality—The Main Goals and Objectives Dealing with Its Preservation in the International Panorama

In light of the environmental challenges the world is now called to face (climate change, biodiversity loss, increasing food demand, just to name a few), it is not unexpected that soil quality is a central focus of the new Green Deal for Europe and the United Nations Sustainable Development Goals, whose main connections with soil quality are reported in Figure 1 [1].

Both initiatives aim to mitigate biodiversity loss, reducing pollution, combating climate change, and promoting a healthy environment and sustainable land utilization [2]. The Soil Mission: a Soil Deal for Europe, among the five strategic missions of the "Research & Innovation" package of the Horizon Europe Program, together with the European Biodiversity Strategy for 2030, the European Soil Strategy for 2030, and indirectly, the European Adaptation Strategy and the Zero Pollution Action Plan must also be mentioned; all these goals pass through the conservation of soil quality, which on the contrary, is still far from being reached at the global scale. Indeed, nowadays, 60–70% of European soils are considered unhealthy as a direct result of current management practices, but also, to a lesser degree, climate change and indirect action of air pollution [2]. Erosion, acidification, contamination, and salinization are considered the primary forms of land degradation [3], which contrasts, by definition, with the possibility of reaching satisfactory soil quality. Human action and pressure are considered the main cause, including uncontrolled soil sealing, urbanization, pollution derived from industrial activities, and unsustainable agricultural practices. In line with international goals, in 2018, the United Nations Convention to Combat Desertification (UNCCD) promoted the Land Degradation Neutrality project, aiming to achieve target 15.1 of the Sustainable Development Goals ("By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements") [4].

Figure 1. Soil quality in the Sustainable Development Goals [1].

Moreover, the need to preserve and protect soil quality is strictly linked to other global priorities, such as the increase in agricultural production, predicted to reach +70% by 2050 due to the increasing world population and demand for food and biofuels [3,5]. While there was a huge evolution of agricultural practices towards more efficient forms of production (the well-known Green Revolution) between the early 1970s and the late 1980s, this paradigm cannot be proposed today. The reason is that sustainable agriculture should be based on limiting the use of chemical inputs and mechanical stress with respect to the past (and still current) situation achieved thanks to the Green Revolution. Now, a Greener Revolution [3,6] is required, based on the sustainable use of soil, the valorization of territorial peculiarities, and the preservation of soil quality. As a matter of fact, the FAO recognized that the loss of organic matter in the soil must not exceed its formation speed as a priority, in addition to promoting agricultural practices that are able to protect, enhance, preserve, and restore biodiversity, to achieve sustainability in the long term [7].

The goals cited above are aimed at preserving soil quality; they arise from the need to decrease soil sealing and land take, which are considered the main cause of soil degradation and subtraction from agriculture, through adequate determination of the key objectives at more local scales. For example, in Italy, at the national level, despite a lengthy parliamentary debate on soil [8] and a National Sustainable Development Strategy (SNSvS), no law has been enacted for soil protection—not at the level of soil consumption due to urbanization, nor towards biodiversity protection. Historically, the importance of soil in spatial planning has been relegated to its role as a foundation for buildings and infrastructures, for geothermal energy, and for the conservation of archaeological and cultural heritage [9], the focus having been traditionally on urban functionality instead of on the urban environment [10]. However, current knowledge shows how most urban and peri-urban functionalities depend on ecosystem services and, as such, on soil quality. In this sense, the ecosystem services (ES) approach proposed by different studies, acting as a bridge between scientific knowledge and policy making, can assist in building effective spatial strategies [11]; for example, in the context of soil degradation, establishing a connection between strategies related to soil ecosystem services (SoES) and spatial planning is essential for creating a framework to prevent, reduce, and reverse the detrimental impacts of soil sealing and land take [12], as the next paragraph will show in detail. Such approaches need a greater awareness of the role of soil at the planning stage, which in turn aids enforcement of soil monitoring in the territory, including biodiversity as well as the processes and main threats to which soils are subjected [13].

In this light, the recent proposal of the Soil Monitoring Law (Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law), COM/2023/416 final) represents a key stage in promoting an effective soil protection strategy at the planning level. Although the novelties and descriptors proposed by the text will be presented in the following sections, it is necessary to emphasize the importance that the proposal places on site-specific monitoring of soil quality through the creation of the so-called Soil Districts, which are intended to be the reference units for soil quality monitoring. Although their size has not yet been defined, the novelty lies in the fact that their boundaries will be established based on the climatic, environmental, pedologic, and prevailing land use conditions of the territory. This approach represents a shift from purely administrative management to an assessment based on the characteristics of the soil [14]. As will be explained below, the proposal in this paper is in line with this approach, aiming to characterize and monitor soil quality at a spatial scale appropriate for the purpose.

Complementary to this, a second European proposal (accepted, with modifications, in July 2023) is worth mentioning, the Nature Restoration Law (Proposal for a Regulation of the European Parliament and of the Council on Nature Restoration, COM/2022/304 final). This proposal aims to introduce binding ecosystem restoration targets for Member States. The overall target is to achieve the restoration of at least 20% of degraded ecosystems, whether marine or terrestrial, by 2030. The link to soil and its protection is recognized in the report, which states that "many terrestrial ecosystems depend on and interact with the underlying soils". Not surprisingly, several articles in the text that propose binding targets for the protection and restoration of ecosystems simultaneously advance an approach to combating soil consumption and restoring its quality [15]. Thus, this proposal serves as a valuable reference for spatial planning.

In this concise introduction to the research topic, we have referred to soil quality, even though the conceptual framework of the analysis is broad and touches on areas not traditionally limited to what is considered soil. The next paragraph will elucidate these aspects.

1.2. Land Quality or Soil Quality? A Literature Review

In 1976, the Food and Agriculture Organization of the United Nations (FAO) defined land as "a wider concept than soil or terrain", since the former comprises "the physical environment, including climate, relief, soils, hydrology and vegetation, to the extent that these influence potential for land use" [16]. Despite this broad definition, the concept of land seems to be viewed from an anthropocentric perspective, as some scholars summarize its role as providing "the basis for land use" and define land quality as "the state or condition of land, including its soil, water and biological properties, relative to human needs" [17]. Even though "purely economic and social characteristics [. . .] are not included in the concept of land" [16], land mediates interactions among "the natural environment, society and the economy" [18]. Ray et al. argue that constructing a land quality index is "more challenging" than a soil quality index due to the need to consider various factors such as "local and regional factors, landform types, risk of erosion, anthropogenic activities and natural conditions, selected socio-economic indicators, crop type and vegetation apart from biophysical factors" [19]. Similarly, Pieri et al. include social and economic measurements among their indicators of land quality, distinguishing it from soil quality [17]. This distinction is underscored by the fact that, unlike soil quality, land quality is often referred to in the plural (land qualities [17]), highlighting its functional role rather than being treated as a concept with its own dignity.

On the other hand, the definition of soil quality is quite flexible; over the decades, the concept of soil quality has evolved within the scientific community. Initially, it was viewed from an anthropocentric perspective, primarily within the agronomic field, but it has since shifted towards a more pedo-centric and "eco-centric" approach [20]. For instance, Mausel's definition is considered one of the earliest in the scientific community, describing soil quality as "the ability of soils to produce corn, soybeans, and wheat under high-level management conditions" [21]. However, Doran and Parkin criticized this production-focused view as too limiting and expanded the concept to include the capacity to promote animal and plant health explicitly within their definition of soil quality [22,23]. Over the years, it has been recognized that soil quality should be evaluated in terms of soil functions [24,25]. Karlen identified five functions related to healthy soils, which can be seen as an initial list of ecosystem services recognized worldwide today (refer to Section 2 for a clearer distinction between soil functions and services): sustaining biological activity, diversity, and productivity; regulating and partitioning water and solute flow; filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials; storing and cycling nutrients and other elements within the Earth's biosphere; providing support for socioeconomic structures and protecting archaeological treasures associated with human habitation. A more recent, concise, and commonly accepted definition is the one proposed by Liu et al., who defined soil quality "the ability of soil to provide a desired outcome for sustaining plant and animal productivity, maintaining or enhancing water and air quality and supporting human health and habitation" [26]. This indicates that the definition is no longer solely anthropocentric, signaling a broader and more inclusive concept than in the past. The concept now encompasses the intricate relationships between soil, other natural systems, and human activities, reflecting a more holistic understanding of soil quality.

Given the historical overlap between soil and land quality, significant insights about their frequency and temporal trends can be gleaned through a literature review using Lens.org research structure (https://www.lens.org/ (accessed on 10 February 2024)), with specific query boundaries imposed. By examining scientific texts that have addressed soil quality and land quality from the 1950s to 2024 (mentioning soil quality or land quality in the title and/or abstract, without any proximity search—meaning no words between soil/land and quality), it becomes evident that soil quality has approximately ten times more results than land quality (41,138 scholarly works vs. 4173). The proportion decreases significantly when considering results solely from EU institutions (almost a 20:1 ratio, 6914 vs. 354) and Italian institutions (almost a 17:1 ratio, 713 vs. 42). Interestingly, this ratio shows an increasing trend over time. For instance, comparing global cases from 1990 to 2024, the ratio shifts from 1:2 to 1:4, indicating that in 2024, the frequency of scholarly works on soil quality versus land quality has doubled compared to 1990 (average annual reduction in works on land quality vs. soil quality from 1965 to 2024: 1.5%.). This trend highlights that the concept of land quality has fallen into disuse in the more recent literature, which tends to refer to soil quality.

A second important consideration concerns the subjects with which these articles are associated. Figure 2 shows with a heatmap the comparison between the top ten subjects of soil quality versus land quality scientific texts from 1965 to 2024. The results clearly show that, proportionally, fields closer to spatial planning (such as "Geography, Planning and Development" in Figure 2) prefer the concept of land quality, whereas soil quality is more commonly associated with agronomic and ecological fields. However, in absolute terms, the results overlap; revisiting the tag Geography, Planning, and Development, it encompasses 370 articles on land quality compared to 1295 on soil quality. Moreover, the percentage gap between the two demonstrates once again a clear increase over time in favor of soil quality scientific texts. This trend is evident even in the field of spatial planning, where in recent years, soil quality articles are nearly double those focused on land quality (see Figure 3).

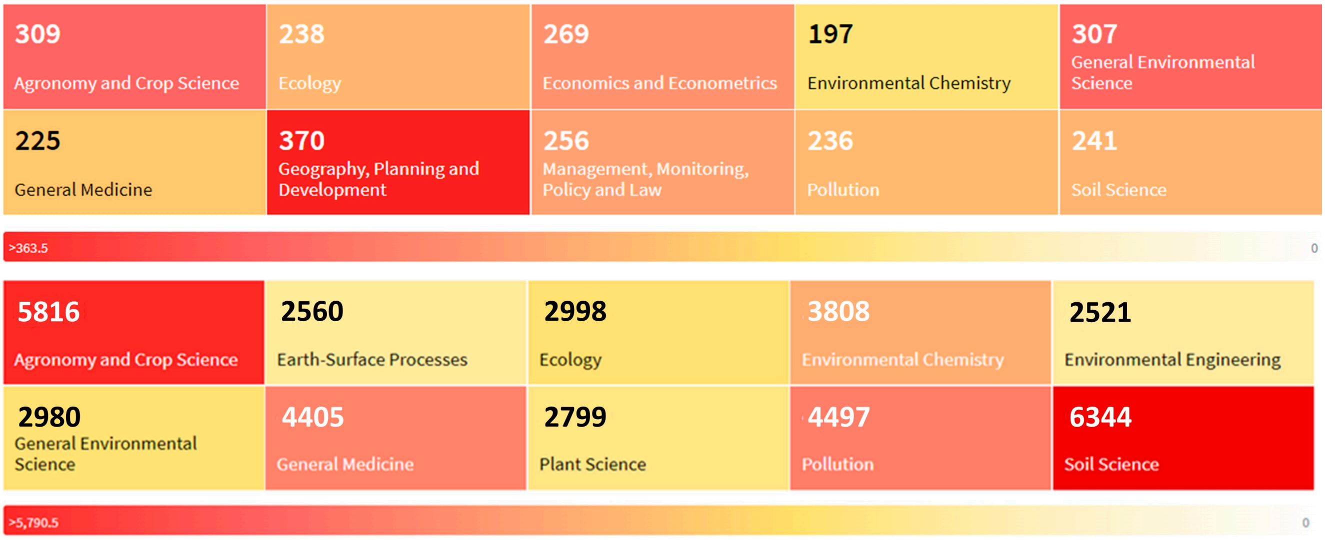

Figure 2. Heatmap detailing, with a chromatic scale, the weight of each subject on the totality of scientific land quality (above) and soil quality scientific texts (below), from 1965 to 2024 on a world basis. The numbers in each cell indicate the absolute number of articles by subject and reveal once again the disproportion between the two classes of results.

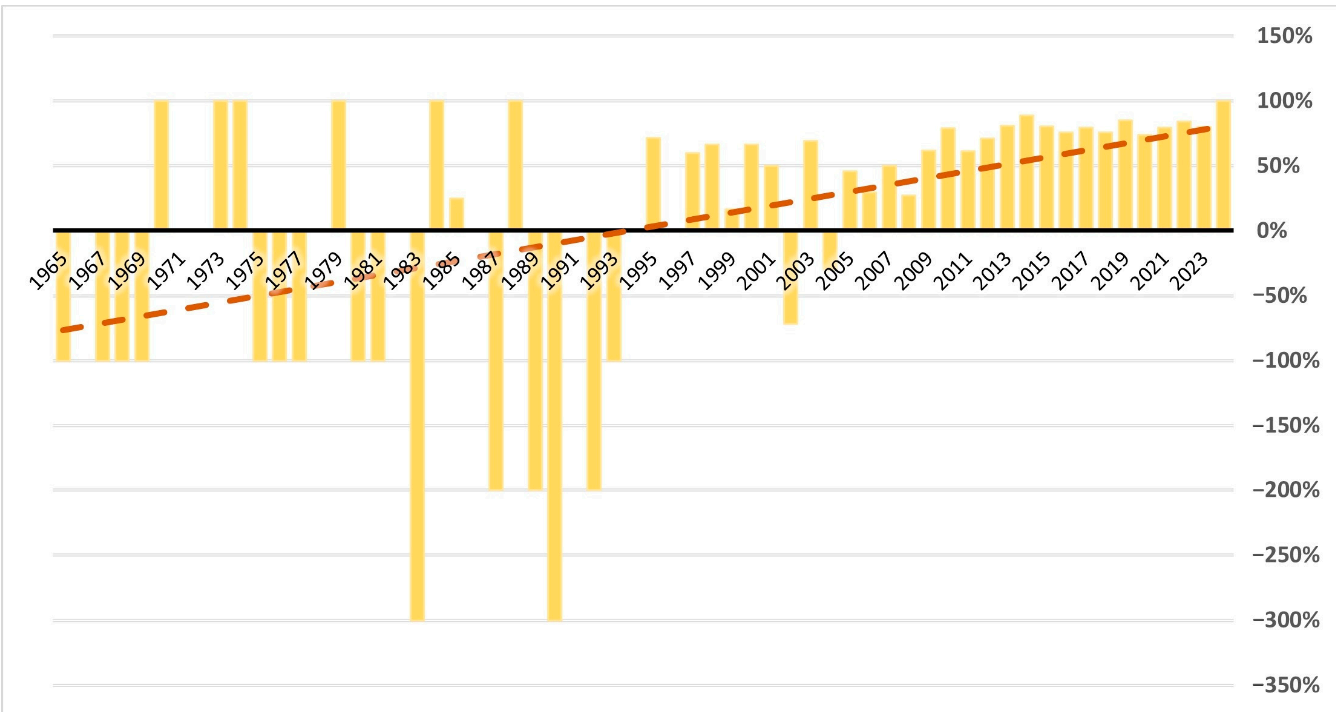

Figure 3. Percentage gap between soil quality and land quality scientific texts, tagged with "Geography, planning and development" subject, from 1965 to 2024 on a world basis (from Lens.org). Negative values stand for years in which land quality articles surpass in absolute terms the number of soil quality articles in the tagged subject. Zero values stand for years in which land quality articles match in absolute terms the number of soil quality articles in the tagged subject. Positive values stand for years in which soil quality articles surpass in absolute terms the number of land quality articles in the tagged subject.

For these reasons, this article will consistently use the term "soil quality", encompassing not only agronomic and pedological aspects but also ecosystemic factors—which, as clarified later, include the cultural and recreational roles of the soil. This decision is justified by the considerations outlined above and summarized as follows:

- Temporally speaking, soil quality is gaining prominence in the literature at the expense of land quality, even within the fields of spatial and strategic planning.
- In absolute terms, the number of scientific texts tagged with soil quality far exceeds those tagged with land quality, even within the fields of spatial and strategic planning, indicating a richer body of literature.
- Traditionally, the term "land quality" has primarily denoted suitability for human uses, such as agricultural or pastoral purposes, reflecting an anthropocentric viewpoint. Over time, however, soil quality, originally associated with pedogenic and agronomic contexts, has evolved to encompass the inherent quality of the soil itself, beyond its practical implications or usefulness for human activities. Moreover, discussions on soil ecosystem services include cultural and recreational services, reflecting a broader conception of the term soil quality under a novel eco-centric perspective compared to the past.

1.3. Face the Problem: How—and Why—to Evaluate the Soil Quality and Degradation at Sub-Regional Scale?

According to the European classification known as the Nomenclature of Territorial Units for Statistics (NUTS) (Regulation (EC) No. 1059/2003 establishing a common classification of territorial units for statistics (NUTS)), the territory can be subdivided into different Territorial Units (NUTS0 for the national level, NUTS1, NUTS2, NUTS3 for the sub national levels) and Local Administrative Units (LAUs). Spatial planning typically follows this hierarchical subdivision, distinguishing different roles suitable for each territorial level. It is important to consider that various European environmental targets adhere to the subsidiarity principle, which delegates the possibility of intervention at the level closest to the citizen [27]. Therefore, these targets require adaptation at the Member State level (NUTS 0) and further down to more local scales to achieve greater effectiveness. For instance, some countries have accelerated the EU objective of achieving zero soil consumption by 2050 to a target of 2030. Consequently, there is a need to adjust local plans, introducing new regulations in land management aimed at reducing land use projections, and promoting the revitalization of urban areas. The main objective is to achieve a quantitative reduction in land consumption, safeguarding the highest-quality soils and promoting a rational and efficient settlement pattern. This issue must be considered within a broader context, particularly concerning land degradation, which some scholars identify as one of the most serious and alarming environmental challenges at global, regional, and local levels [28]. Among its most severe manifestations is soil sealing, recognized as the most detrimental [29]. To trace some of the steps taken by the EU in addressing this issue through planning strategies, it is worth mentioning the 2012 guidelines on best practices to limit, mitigate, or compensate soil sealing. These guidelines emphasize the urgency of assessing soil quality across the territories to guide inevitable land use transformations towards lower-quality soils, thereby safeguarding soils classified as high or very high in terms of quality and functionality. The guidelines explicitly state that "urban development should target low-quality land based on an urban planning map" and priority should be given to the "conservation of urban and peri-urban agricultural land" [30]. Again, in 2014, the EU published a study assessing the feasibility of establishing a framework to measure progress towards more sustainable land use [31]. However, a precise and standardized framework for evaluating soil quality in planning dynamics is still lacking [30,32–34]. Notably, the city of Stuttgart [34], as well as Germany [32], along with Tuscany and Bolzano [30], serve as exemplary cases for voluntarily incorporating guidelines that consider soil quality in spatial planning initiatives.. Consistently, the SOS4Life project (https://www.sos4life.it/ (accessed on 17 December 2023)) states that "if the limitation of land consumption must be established at a regulatory level (European, state, regional) there are, however, some tools that can be used to increase the level of knowledge on land consumption and to increase awareness of its effects (to therefore stimulate a legislative response to the problem)". One crucial tool is the creation of a soil quality evaluation map over the territory, since it could "contribute to land consumption limitation strategies if, when drafting municipal planning regulations, the information on the value of the land it provides is taken into account and if this leads, for example, to imposing a restriction on the transformation of soils that are of better quality" [34]. In this sense, the map would serve a mitigation function by directing land consumption towards less valuable areas, thereby reducing its impact [34]. But it could also serve another purpose; as stated by SOS4Life, a soil quality evaluation across the territory could potentially serve a compensation function through the de-sealing measures [34]. In this regard, a soil quality map could facilitate qualitative compensation for soil sealing, not just quantitative. However, such applications are currently limited in European contexts [34], which is why this research will primarily focus on the mitigation potential of soil quality assessment.

The urgency in detecting soil quality is enforced by the actual context of increasingly rampant urbanization, evidenced by publicly available data on land consumption across various regions. Addressing this issue requires a comprehensive perspective beyond the confines of municipal boundaries and local dynamics, necessitating an overall vision of a wide area and at a sub-regional level (approximately NUT3). This approach is more detailed and site-specific compared to regional scales (NUT2). Therefore, the objective of this paper is to pinpoint, underline, and address the existing gap in sub-regional (NUT3) soil quality assessment by delineating a comprehensive set of indicators. These indicators are crucial for assessing soil quality at a sub-regional scale, facilitating a more comprehensive understanding of soil characteristics, functions, services, and vulnerabilities. Moreover, the objective is to promote conscious efforts in safeguarding the soil from degradation and excessive consumption. The coordination and strategic function of sub-regional planning can effectively bolster organic and integrated wide-area planning. In doing so, it serves as an independent and authoritative guide, highlighting supra-municipal issues that intersect with local interests, particularly in areas such as soil sealing and territorial and landscape preservation [35]. Thus, the paper presents a methodology to assess the current framework and indicators related to soil quality. Following this, it aims to test the applicability of these methods in a specific case study within a province (NUT3) in Italy.

2. Materials and Methods

In light of the points made in Section 1 and with the aim of providing a wide range of soil quality indicators (referring to both indicators and indices) for the spatial context of reference, the first step is to conduct a search for existing proposals and methodologies. This search should encompass not only the scientific community, but also legal acts, technical, programmatic, policy, and assessment documents at various institutional levels. More specifically, and as will be better discussed in the following sections, the initial evaluation should involve the indicators proposed by the recent directives, regulations, or guidelines, such as the already mentioned Soil Monitoring Law and Nature Restoration Law. Again, in an international context, an analysis of the dedicated scientific literature should be conducted to understand how the issue of soil quality has been evaluated by scholars over the decades. The research must also involve more localized evaluations, from the European to the national and down to more local contexts, through an analysis of institutional legal acts and technical and assessment reports.

The second step involves searching for data to characterize the identified indicators at an appropriate spatial scale for sub-regional assessment, verifying the availability from European, national, and local institutional databases. The search for indicators and data is guided in the proposed methodology by the intent to detect soil quality with a holistic and multifunctional approach, evaluating not only the soil characteristics in physical, chemical, and hydraulic terms (namely the soil properties essential for deciding about the best soil usage in a specific area), but also the services it provides, e.g., in ecological, cultural, and aesthetic terms and the vulnerabilities it is subjected to concerning the main threats.

Thirdly, the outcomes of the previous steps were cross-combined to obtain a list of indicators adequate for the scale of interest, specifically those for which available data were found for the sub-regional characterization of soil quality.

To clarify the link between methodological phases and the outcomes, Section 3 presents tables with headers color-coded according to the steps ("Phases"), as reported in Figure 4.

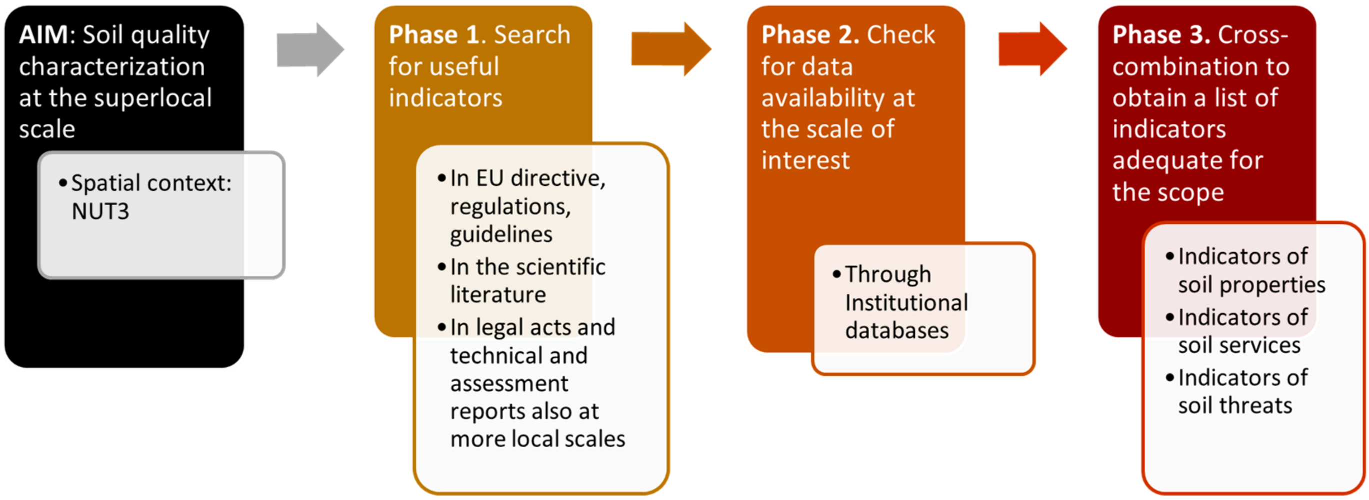

Figure 4. The method discretized by steps.

Clearly, in each State, the potential indicators and databases for soil quality detection differ, and the same applies for more local scales, requiring a desk analysis at the NUTS0, NUTS1, NUTS2, NUTS3, and when possible, LAU level.

The phases of the proposed method are shown in Figure 4.

The sources to be considered for the analysis should cover all European and supra-local territorial levels (NUT0, NUT1, NUT2) from the furthest to the nearest to the local level. Additionally, the origin of such materials may be legislative (regulatory or policy), academic, planning (general or sector plans), or specific projects (e.g., European projects). Indicators available from all sources must be organized to be comprehensible. This organization must be structured according to the principles of aggregation. The sources will then be organized by typology (reference law, project, bibliographic source, plan).

The indicators will be presented according to soil properties, soil services, and soil threats, drawing insight from diverse references [22,36,37]. Starting from the literature review carried out by Bünemann [22], it is evident that the distinction between soil functions and services is weak. This distinction is not functional for our research purposes, so we decided to refer solely to ecosystem services and exclude ecosystem functions, as the two terms are very similar from a planning perspective. Specifically, soil functions refer to the processes that form the basis of ecosystem services, i.e., the link between properties ("what soil is") and ecosystem services ("what soil can do"). In contrast, soil services call for an "inter- and transdisciplinary approach" and are more widespread in the literature [22,36].

From the agronomic perspective [38], when dealing with soil quality indicators, scholars tend to focus solely on the category of soil properties, assuming that all the other aspects (such as services and threats) can be characterized based on the state or variation in soil properties. However, from the perspective of spatial planners, this direct relationship between soil properties and services/threats is considered overly detailed. Therefore, in this study, these three categories of indicators (soil properties, services, and threats) were considered separately. Yet, soil properties must be retained as a category, since this information provides insights into soil characteristics from a sectorial perspective (e.g., agronomic or geotechnical). Additionally, with expert support, it may be possible to derive information about soil services and threats from soil properties when needed. For all these reasons, from the spatial planning perspective and acknowledging the scarcity of (open) data sources, this three-fold categorization is, to our knowledge, the most effective.

The three indicators' categories are thus defined as follows:

- Indicators of soil properties are considered to be "the physical (e.g., porosity, texture), chemical (e.g., pH, readily available phosphate), and biological (e.g., microbial biomass) characteristics of a soil" [37].
- Indicators of soil services provide information about soil's utility and importance for the surrounding environment and ecosystems, as well as human activities. This includes "not only [. . .] the provision of goods and services related to the intended land use (e.g., production services such as food and wood production) but also [. . .] goods and services such as the provision of aesthetic beauty, cultural heritage and preservation of biodiversity" [39].
- Indicators related to main current and potential threats for soil quality over the territory show the consequential effects of human pressures and soil's intrinsic and extrinsic vulnerability and sensitivity to them.

The three categories mutually influence each other, as soil properties determine ecosystem services and are influenced in turn by soil threats. This classification aligns with the DPSIR (driver–pressure–state–impact–response) framework [40], particularly the PSR (pressure–state–response) version. Here, pressures correspond to "land use and management and the associated soil threats", state refers to soil properties (the state of the soil), and response can be evaluated in terms of the services and goods provided by the soil [22].

The presence of soil quality indicators in scientific studies and laws does not guarantee their real availability. Therefore, the availability of data (primarily open-source and secondarily paid) must be verified indicator by indicator, considering the scale of reference and the intended purpose of the database.

Combining the potential indicators and available datasets, it was possible to compile the final list of indicators adequate for the soil quality sub-regional characterization in a specific territorial level. This list intends to specify, in addition to the reference category of the indicator, the detailed description of the indicator, the available dataset, and its reference spatial scale. The outcomes are presented in Section 3, where for each phase, the tables show "Useful indicators" (Phase 1), "Data availability" (Phase 2), and "Cross-combination" (Phase 3) outputs, as presented in Figure 4.

A critical and integrated reading of data sources—open-source databases at different scales—from the spatial planning perspective is essential. The related disciplines often do not conduct in situ sampling but rather verify the availability of information to achieve comprehensive and homogeneous coverage of the territory. This approach facilitates the description of its evolution through key parameters, enables strategic planning of interventions, and supports policymakers.

3. Results

The foundation of the Soil Monitoring Law proposal lies in establishing a clear and unified definition of soil quality and identifying common descriptors to assess and determine soil health. Moreover, it calls for the development of remote sensing systems and programs tailored for this purpose. As previously mentioned, the proposal specifies that the Commission is enhancing these services through the Copernicus program. This initiative aims to monitor key soil quality descriptors effectively and also includes investments to strengthen the LUCAS program [14]. Specifically, the Soil Monitoring Law defines healthy soils as those "in good chemical, biological and physical condition so that they can provide ecosystem services that are vital to humans and the environment, such as safe, nutritious and sufficient food, biomass, clean water, nutrients cycling, carbon storage and a habitat for biodiversity" [14]. Accordingly, soil quality is assessed and measured based on the ecosystem services it can sustain. Consistent with this goal, the soil quality descriptors proposed by the European Commission aim to quantify the potential loss of ecosystem services by analyzing the impacts of primary threats (as previously outlined in Section 1): salinization, erosion, organic carbon lost, subsoil compaction, excess of nutrients, contamination, topsoil compaction, acidification, loss of biodiversity, and reduced water retention capacity [14].

Regarding the Nature Restoration Law, as previously noted, it includes various articles that, in conjunction with the goal of protecting and restoring ecosystems, contribute to combating soil consumption and safeguarding soil quality. Together with targets, many indicators are proposed to monitor the quality of the indagated ecosystems. Specifically, Articles 9 and 10 address the restoration of agricultural and forest ecosystems, providing a list of indicators that emphasize monitoring both subsoil and upper soil biodiversity [14]. It is worth noting that the document, as approved on 12 July 2023, has undergone numerous modifications, particularly in the articles most relevant to the present analysis. Article 9 has been completely removed, along with the instruction to monitor the respective indicators. Nonetheless, the following sections will refer to the proposed text in its more complete form, as evaluating the compromises made during the approval phase that influence the document's evolution is beyond the scope of this discussion.

Regarding the literature review conducted, it has helped to explicate, at least partially, the intricate web of relationships that mutually link the various soil parameters and properties. Among the selected descriptors, there are indicators addressing aspects more directly related to the chemical and physical characteristics of the soil (physical, chemical, hydraulic, and water quality indicators), the life it harbors and sustains (biological indicators), and its productivity (fertility indicators). Much less common in the literature is the approach of defining soil quality in relation to humans and anthropogenic activities other than agriculture. This includes the varied functions that soil performs relative to human use (cultural, anthropogenic, and landscape indicators), as well as its relationship with the environment and neighboring ecosystems (naturalistic and ecological indicators), and the valuation of the ecosystem services provided by soils. The latter, in particular, was evaluated by the present analysis with reference to the findings of the European project LIFE + Making Good Natura, summarized by Schirpke et al. [41].

According to Section 2, the following Table 1 reports the indicators about soil quality at the European level organized by typology of source:

- Laws and proposals at the European scale (Soil Monitoring Law and Nature restoration Law);
- Scientific literature;
- European project: LIFE + MGN.

The table also reports for each source typology the precise reference source from which indicators have been selected. In the following list of indicators, the categorization introduced in the previous section is already evident, including soil property indicators (e.g., electrical conductivity), soil services (e.g., total amount of fodder produced), and soil threats (e.g., soil erosion rate). Please note that the header of the table refers to the correspondence between colors and methodological steps, as presented in Figure 4.

Table 1. An initial list of indicators proposed at the European level and considered useful for characterizing soil quality.

Source Typology	Reference Source	Indicator
Laws and proposals at the EU scale	Soil Monitoring Law [14]	Electrical Conductivity (EC)
		Soil Erosion Rate
		Soil Organic Carbon (SOC) concentration
		Bulk density in topsoil
		Bulk density in subsoil
		Soil water holding capacity of the soil sample
		Concentration of Heavy Metals in Soils, such as As, Sb, Cd, Co, Cr (total), Cr (VI), Cu, Hg, Pb, Ni, Tl, V, Zn
		Extractable Phosphorus
		Nitrogen in soil
		Soil Acidity
		Bulk Density in Topsoil (A horizon)
		Basal Soil Respiration
	Nature Restoration Law [15]	Common Butterfly Index
		Stock of Organic Carbon in Cultivated Mineral Soils
		Percentage of Agricultural Land Affected by Landscape Elements with High Diversity
		Standing Deadwood
		Downed Deadwood
		Percentage of Forests with Unevenly aged Structure
		Forest Connectivity
		Common Bird Index in Forest Habitat
		Stock of Organic Carbon
		Percentage of Forests Dominated by Native Tree Species
		Tree Species Diversity
Scientific literature review	[42]	Texture, humidity, temperature
	[43]	Texture, bulk density and Water Holding Capacity (WHC)
	[44]	Texture, bulk density, Available Water Capacity (AWC)
	[45]	Texture
	[46]	Texture, depth, slope, bulk density, Water Holding Capacity (WHC), Hydraulic conductivity (HC)
	[47]	Texture, depth, slope, surface stoniness, hardpan, Hydraulic conductivity (HC), drainage conditions
	[48]	Particle size distribution and sand, silt, clay content (namely, the texture), bulk density, Electrical conductivity (EC), coarse fragments, soil structure type, Munsell color
	[42]	pH, Electrical conductivity (EC), Soil Organic Matter (SOM), Corg/Norg
	[43]	pH, Cation exchange capacity (CEC), Electrical conductivity (EC), Organic carbon, total and mineral nitrogen, available K, Ca, Mg, and P contents and total Cd, Cr, Cu, Pb, and Zn contents
	[49]	pH-H20, pH-$CaCl_2$, Electrical conductivity (EC), Cation exchange capacity (CEC), exchangeable cations, Exchangeable sodium percentage (ESP), Sodium adsorption ratio (SAR), and calcium carbonate equivalent (CCE), just in arid environments

Table 1. *Cont.*

Source Typology	Reference Source	Indicator
	[47]	pH, salinity, Exchangeable Sodium Percent (ESP), $CaCO_3$ content
	[46]	pH, Electrical conductivity (EC), Electric Conductivity groundwater, Cation exchange capacity (CEC), Exchangeable sodium percentage (ESP), OM (organic matter), $CaCO_3$ content, gypsum content
	[45]	$CaCO_3$ content, Cation exchange capacity (CEC), Electrical conductivity (EC), Exchangeable sodium percentage (ESP), and Sodium adsorption ratio (SAR)
	[48]	Total nitrogen, K, Ca, Mg, P, $CaCO_3$, Fe_2O_3, pH, Leaf Nitrogen Concentration (LNC), Calcium carbonate equivalent (CCE), Soil exchangeable potassium (Kex)
	[50]	Dehydrogenase Activity (DHA)
	[47]	Available N, P, K (macro nutrients), Zn, and Soil Organic Matter (SOM content)
	[46]	Available N, P, K, Fe, Zn, Mn, Cu
	[51]	Soil Organic Carbon (SOC), available phosphorus (AP), C:P ratio
	[42]	Soil Organic Matter (SOM) and its variation, Microbial biomass
	[43]	Microbial biomass, fungal mycelium, soil potential respiration, and potentially mineralizable nitrogen
	[52]	Microbial biomass and its activity, soil enzymatic activities, N mineralization rates, soil respiration, ratios of bacteria to fungi, Gram-negative to Gram-positive bacteria, relative proportions of various functional groups of soil fauna
	[53]	Bioindicators, as the presence of oribateans, collemboles, nematodes, beetles
	[45]	Soil Organic Matter (SOM content)
	[48]	Soil Organic Carbon (SOC content), Soil Organic Matter (SOM content), labile organic carbon, soil microbial respiration
	[45]	Wilting point, Field capacity, Bulk density, Saturation, Saturation hydraulic conductivity, Available Water Content
	[54]	Water Stable Aggregate percentage (WSA), bulk density, Permanent Wilting Point (θPWP), field capacity measured on repacked and intact cores, saturated hydraulic conductivity (KS), and Soil Organic Carbon (SOC)
	[55]	Soil filtering capacity
	[1]	Soil erosion
European project: LIFE + MGN	[41]	Total amount of fodder produced
		Total potential number of animals that can be hunted/fished
		Harvested wood
		Total production of mushrooms
		Amount of forest seed harvested
		Water captured from springs and wells of the catchments recharged by the site
		Carbon dioxide stored/sequestrated in vegetation
		Water infiltration
		Avoided erosion potential
		Water retention

Table 1. *Cont.*

Source Typology	Reference Source	Indicator
		Rare species
		Appealing landscape
		Recreational activities
		Cultural elements

3.1. Data Reference Sources and Their Availability/Usability Referring to the Different Scales

Although data collected on the topic of soil quality are usually the result of in situ sampling (also required by the Soil Monitoring Law), soil science has increasingly begun to produce maps and databases at different scales that come to meet the spatial data needs of policymakers and planners [56,57]. This development has been facilitated by remote sensing techniques for detecting qualitative–quantitative soil quality parameters [58,59]. Consequently, there is now a wide selection of open-source data that is easily updatable and features increasingly refined spatial resolutions, which can be used for the assessment of canonical indicators from the literature and beyond.

The databases chosen as a reference for the EU level are reported in Table 2 with concise descriptions and information on the administrative level of the institutional database used. Please note that the header of the table refers to the correspondence between colors and methodological steps, as presented in Figure 4.

Table 2. The main databases consulted for the data availability check at the European level.

Database Administrative Level	Dataset	Description
European and global data sources	Copernicus Land Monitoring Service (https://land.copernicus.eu/en (accessed on 20 November 2023))	It provides, among other resources, the main international reference for land use classification, known as Corine Land Cover, with the latest update in 2018.
	Euro-Mediterranean Centre on Climate Change (CMCC) (https://www.cmcc.it/it (accessed on 21 November 2023))	This is a scientific research facility working in the field of climate science, developing high-resolution simulations using global Earth system models and regional models, with a focus on the Mediterranean area. Among the various predictions provided are climate, bioclimate, and soil erosivity forecasts.
	European Soil Data Centre (https://esdac.jrc.ec.europa.eu/ (accessed on 10 December 2023))	It is the primary European reference source for soil quality determination, offering comprehensive mapping of chemical, physical, biological, and other properties, primarily derived from sampling conducted at the European scale within the LUCAS program. The database is extensive; however, for this analysis, only sources with a spatial resolution of less than 1 km × 1 km are considered, as they are adequate for the paper's purpose of supra-local characterization.
	European Butterfly Monitoring Scheme (https://butterfly-monitoring.net/it (accessed on 5 December 2023))	The project implements standardized methods of annual field monitoring of butterfly presence. Italy, specifically, has participated in the ABLE project, which introduced a new monitoring scheme for target butterfly species starting from 2018.

3.2. Presentation of the Case Study: The Lombardy Region and the Province of Brescia

Italy operates under a four-tier governance system: national, regional, provincial, and local, corresponding respectively to the NUTS0, 2, 3, and LAU levels; in Italy, the NUTS1 level does not correspond to any administrative authority. A clarification on the organization of spatial planning at the Italian level is necessary. Spatial planning in

Italy moves under a bidirectional impulse. Firstly, it adheres to the subsidiarity principle, emphasizing the execution of public functions at the level closest to the citizen, thus that of the municipalities. Concurrently, it involves higher levels of authority (provincial and regional), which provide strategic guidance for territorial development [60]. If the regional authority primarily holds a legislative role in the planning, the provincial authority assumes responsibility for coordinating municipal decisions and offering a comprehensive strategic vision at a wider geographical scale. This role becomes crucial in addressing soil sealing and landscape preservation, which inherently involve sub-regional dynamics. Ultimately, it is the local municipality that has cogency over the soil regime.

According to the annual SNPA Report, soil consumption in Italy continues to transform the national territory at high and increasing rates, with an average in 2022 of 21 hectares consumed per day, the highest in the past 11 years, in which it had never exceeded 20 hectares [61]. This increase is particularly concentrated in specific regions, notably the Po Valley, where Lombardy and Veneto exhibit the highest intensity. Lombardy, in particular, leads in both total soil consumed, accounting for over 290 thousand hectares of artificial land (13.5 percent of Italy's total), and in the rate of land consumption, showing an increase of 908 hectares compared to the previous year [61]. In the Province of Brescia, soil consumption showed a significant slowdown in 2021–2022, increasing by +131 hectares compared to the +307 hectares of 2020–2021 [61,62]. However, the total soil consumed in 2022 remains the highest in the region, nearly equivalent to that in the Province of Milan, which exceeds 50 thousand hectares. This supremacy is reached despite a substantial portion of the province being unsuitable for consumption due to morphological reasons, highlighting an uncontrolled and disproportionate trend in previous years [61]. Given the territorial context, there is a critical need to implement systems that raise awareness about the pivotal role of soil and promote its valorization as a valuable resource. This is crucial for ensuring effective soil protection.

Non-coincidentally, the focus of the case study is the Lombardy Region (NUTS2 level), specifically the Brescia Province (NUTS3 level). Figure 5 illustrates the administrative framework of the NUT3 unit of Brescia within the European and national context.

The selection of Lombardy as the focus is informed by its significant economic stature, comparable to that of a small state. In 2020, Lombardy ranked as Italy's foremost region in economic importance, contributing one-fifth of the national GDP (ISTAT data, https://www.istat.it/it/archivio/265014 (accessed on 20 December 2023)). Moreover, Lombardy boasts the highest resident population in Italy (ISTAT data, https://www.istat.it/it/archivio/267895 (accessed on 20 December 2023)). The region's extensive database of georeferenced territorial data further enhances its suitability as a case study context.

Currently, in Lombardy, there exists a recognition of the possibility to assess the quality of vacant soils at the provincial and municipal (respectively, NUTS3 and LAU) levels through specialized and comprehensive studies. However, municipalities still have the option to rely on regional maps and monitoring systems without further developing and deepening their own knowledge base on the ground [63]. It is unsurprising that, given the current situation, the majority of municipalities choose to align their local soil quality maps, known as Land Use Maps [63], with regional ones [64]. Nevertheless, this approach often results in a superficial, site-specific analysis that lacks thoroughness and accuracy. Furthermore, the decision to select Brescia Province as a case study is primarily motivated by the heterogeneous nature of its territory. This choice requires a comprehensive and varied approach to selecting indicators. At the same time, it necessitates a site-specific refinement of these indicators, tailored to the distinctive characteristics of the local landscape. Figure 6 offers a territorial representation of Brescia Province.

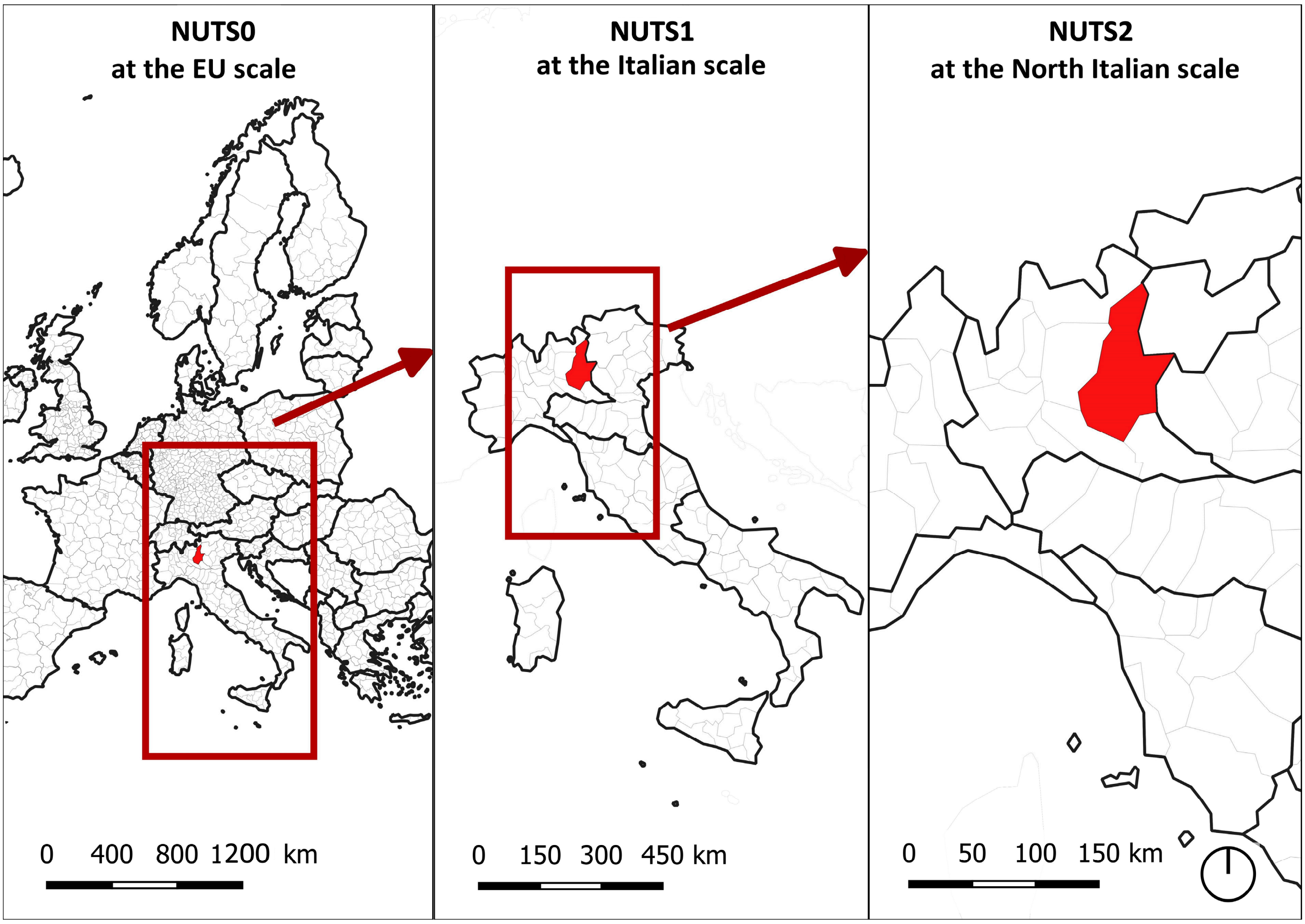

Figure 5. Administrative framework of the reference unit of this analysis (Brescia Province, NUT3).

In addition, by decree of the president of the province in February 2020, the process of aligning the Provincial Plan (Piano Territoriale di Coordinamento Provinciale—PTCP) with the Regional Territorial Plan (Piano Territoriale Regionale—PTR) has started in Brescia Province, as stipulated by Regional Law 31/2014 (Regional Law 28 November 2014, n. 31. Disposizioni per la riduzione del consumo di suolo e per la riqualificazione del suolo degradato. Regulations for the reduction of land consumption and redevelopment of degraded land. Lombardy Region). The PTCP is accompanied by the Strategic Environmental Assessment (SEA) procedure [63,65].

Given the strategic importance attributed to sub-regional (NUTS3) characterization, particularly in light of the updating opportunity provided by the PTCP of Brescia Province, there is an urgent need to develop provincial-level cartography. This process requires the application of clear criteria initially set by the region, involving a comprehensive and meticulous assessment of soil quality across the territory. The objective is to establish a nuanced value system specific to this or smaller macro-areas, focusing on soil protection. Subsequently, municipalities could adopt this provincial-level characterization as a crucial and irreplaceable reference point, laying the groundwork for the creation of more detailed Land Use Maps at the local scale.

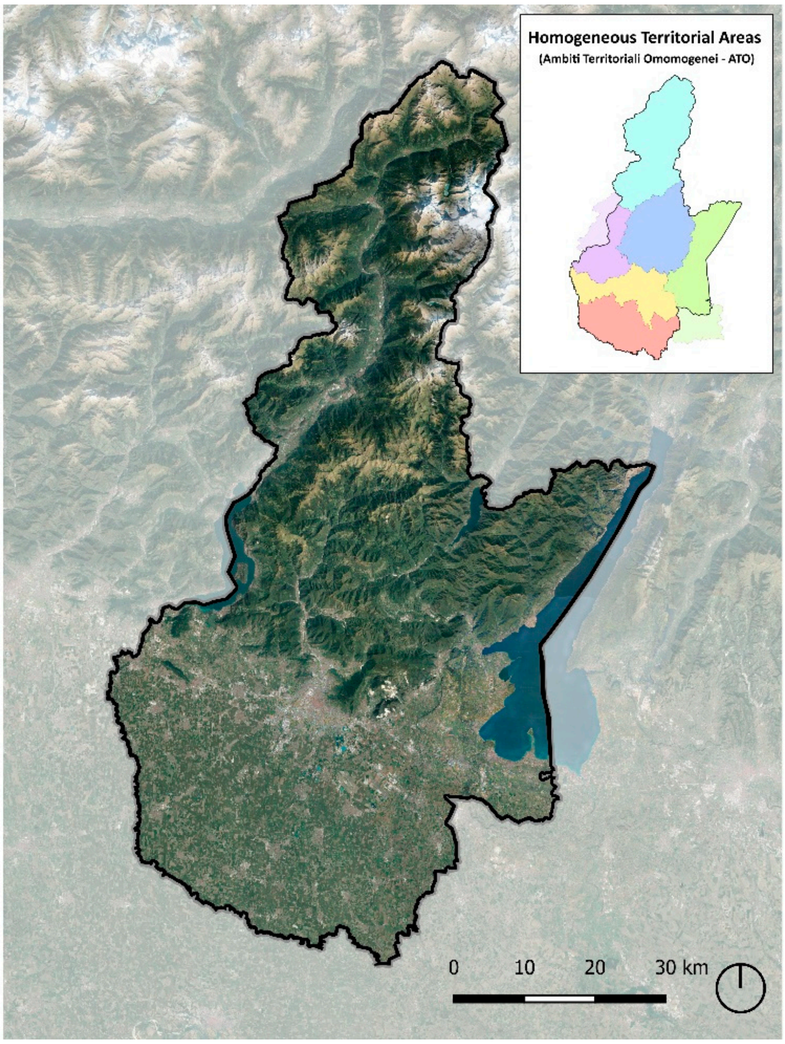

Figure 6. Territorial and morphological framework of Brescia Province, from which emerges its heterogeneity and Homogeneous Territorial Areas (Ambiti Territoriali Omomogenei—ATO) classification.

3.3. Methodology Application

The application of the method discussed above for the case study enabled the compilation of a suitable list of indicators essential for the sub-regional soil quality assessment in Brescia Province. Specifically, it was necessary to deepen the search for indicators and datasets at more local scale (NUTS0, 2, and 3) than previously detailed in the earlier sections (Tables 1 and 2), to achieve a more specific characterization.

For the selection of indicators (Phase 1, as discussed in Section 2), some proposals originate from legal acts, technical documents, and assessment reports issued by the Lombardy Region itself. They regard, for example, the so-called spatial indicators identified by the Strategic Environmental Assessment (SEA) of the 2021 PTR update, which includes the entire new landscape section of the plan. Specifically, these indicators focus on assessing the landscape's vulnerability and resilience to general anthropogenic pressures. They are designed to evaluate factors such as land use, demographic trends, and infrastructural intensity [65]. In addition, regarding more localized pressures, Annex 5 to the D.d.g. of 7 May 2007 [66] from the Lombardy Region provides three additional indicators for assessing the impact of road infrastructures on the territory. These indicators consider the initial naturalness of the area, its sensitivity to pressures, and its potential for restoration post-impact [66]. Another important suggestion is represented by High Nature Value (HNV) farming, adopted by the Lombardy Region, which specifically characterizes agricultural areas with high naturalistic value [67]. These findings are detailed in Table 3, structured similarly to the European level, indicating the source typology (solely institutional legal acts and technical and assessment reports at local scales, as depicted in Figure 4), and the specific reference source from which indicators have been selected. Please note that the header of the tables refers to the correspondence between colors and methodological steps, as presented in Figure 4.

Table 3. An initial list of indicators proposed at national and sub-regional level and considered useful for characterizing soil quality.

Reference Source	Indicator
[65]	Matrix Habitat standard per capita Drainage area index (Idren) Landscape compromise index Territorial biopotentiality Infrastructure fragmentation index
[66]	Index of sensitivity to nutrient and pollutant input Overall naturalistic value index Recovery time factor
[67]	HNV farming

Regarding the available dataset (Phase 2), in Table 4 are reported some local institutional data sources essential for the conducted study. Each entry includes a brief description and specifies the administrative level of reference. These datasets complement the European datasets listed and discussed in the previous Table 2, providing more localized insights. Please note that the header of the table refers to the correspondence between colors and methodological steps, as presented in Figure 4.

Table 4. The main databases consulted for the data availability check at the local and sub-regional scale in Brescia Province.

Database Administrative Level	Dataset	Description
Italian data sources	Italian Ornitological Monitoring, MITO200 (https://mito2000.it/ (accessed on 5 December 2023))	The primary objective of the MITO2000 Project is to establish population indices as part of nationwide projects for individual species or groups of commonly breeding birds across Italy. The initiative contributes to monitoring trends in avian populations over time as part of the Pan European Common Bird Monitoring program promoted by the European Bird Census.
	National Inventory of Forests and Forest Carbon Sinks, INFCC (https://www.inventarioforestale.org/it/ (accessed on 15 December 2023))	Maps and diagrams illustrating the primary characteristics of Italian forests are provided, categorized into thematic groups. These resources offer the option to examine data specific to individual inventory points. Presently, the data provided derive from the third Italian National Forest Inventory conducted in 2015.
	Geoportal of Lombardy Region (https://www.regione.lombardia.it/wps/portal/istituzionale/ (accessed on 20 January 2024))	The Geoportal of the Lombardy Region offers a wealth of resources for assessing the quality and value of soils from an agricultural, ecological, naturalistic, landscape, and cultural point of view. Notably, it includes the Soil Information Bases layer, which provides soil maps at various scales. Additionally, the Geoportal maps Natura 2000 Sites, Protected Areas, forested areas, the Regional Ecological Network.

Table 4. *Cont.*

Database Administrative Level	Dataset	Description
Data sources from Lombardy Region	LOSAN database from Regional Board of Agriculture and Forestry Services (ERSAF) (https://losan.ersaflombardia.it/ (accessed on 28 November 2023))	The proposed dataset comprises approximately 4000 sampling points and provides detailed information categorized by different soil horizons. It includes specific descriptors such as depth, Munsell color, texture, structure, pH, $CaCO_3$ content, and also organic matter content (C and SO). Additionally, exchange elements such as calcium, magnesium, potassium, sodium, aluminum, cation exchange capacity, and saturation rates in bases are documented. The data are not only geo-referenced, but are also organized by geographic sub-environment and report qualitative information on the sampling point, which can then be accessed as needed by municipal offices.
	Regional Environmental Protection Agency (ARPA) (https://www.arpalombardia.it/ (accessed on 29 November 2023))	ARPA Lombardy plays a crucial role in environmental prevention and protection, collaborating closely with regional and local institutions across various activities. These include ongoing planning and management of environmental monitoring across different compartments. ARPA conducts inspections, surveys, and sampling and performs detailed analysis and data processing based on monitoring outcomes. Continuous reporting and control are also part of their responsibilities. However, the data collected by ARPA Lombardy are discrete, meaning they are obtained at specific points rather than continuously across the entire region. As a result, the sampling points may be too sparse to generate reliable interpolation mapping for detailed spatial analysis.
	Regional Observatory for Biodiversity (Ministry of Environment and Land and Sea Protection) (https://www.biodiversita.lombardia.it/ (accessed on 2 December 2023))	Established by DM of the Ministry of Environment and Land and Sea Protection dated 6 June 2011, this system offers a collection of geo-referenced point data containing historical observations of various flora and fauna species.
Data sources from Brescia Province	Geoportal of Brescia Province (https://sit.provincia.brescia.it/ (accessed on 23 January 2024))	The Geoportal of the Province of Brescia represents the closest resource to the territorial scale of reference for the present analysis (precisely local and sub-regional). Among other resources, it includes interactive maps referring to the Provincial Territorial Coordination Plan, updated in 2014.

3.4. Indicator Selection

At this stage, by combining potential indicators (Tables 1 and 3) and datasets (Tables 2 and 4), the final list of indicators suitable for sub-regional soil quality characterization in Brescia Province was compiled (Phase 3). The indicators are detailed in the following subsections: Soil Properties, Soil Services, and Soil Threats. Please note that the header of the tables refers to the correspondence between colors and methodological steps, as presented in Figure 4.

3.4.1. Soil Properties

Table 5 reports the indicators selected for the sub-regional characterization of soil properties, with the specific data reference. Resources and sources included in the list of soil property indicators are in some cases identifiable more properly with data, but are considered indicators since they are presented with a specific purpose of critical evaluation of soil characteristics. In addition, this choice of generalization allows maintaining consistency of classification with the subsequent categories (i.e., indicators of services and threats). In summary, the following indicators have been selected:

- Electric conductivity. It is a soil property related to the soluble nutrients, both anions and cations. It is positively related to good nutrient availability for plants. When lacking, soils can present an unstable structure and a tendency to dispersion, while its abundance can bring salinity problems [68].
- Soil Organic Carbon. It is one of the most indicative soil properties, as it is related to microbial processes, nutrient storage, plant available water capacity, infiltration capability, aggregate formation and stability, bulk density, cation exchange capacity and soil enzymes, and invertebrate presence. It also influences soil erosion tendency, soil structure, and other physical properties [69].
- Bulk density in topsoil and subsoil. Bulk density is an indicator of soil porosity, carbon, and moisture content and, consequently, soil productivity and quality. It is related to various physical, chemical, and biological properties of soil and depends on several factors, including anthropogenic ones. It is one of the most significant indicators for detailing thermophysical characteristics and agricultural production [70].
- Available P. Phosphorus is a crucial macronutrient essential for plant growth and metabolism. Most plant activities, including growth, respiration, and reproduction, hinge on phosphorus levels in the soil. Furthermore, phosphorus is a vital component of photosynthesis. It is correlated with other properties, e.g., soils rich in organic matter offer superior organic phosphate supplies for plant uptake compared to soils with lower organic content. Additionally, soils with minimal leaching contain higher phosphorus levels compared to soils experiencing more significant leaching [71].
- Available N. It refers to the nitrogen availability for plants in soils, necessary for crop production. It depends on the rate of N mineralization, namely microbial decomposition, which is controlled by many environmental factors, such as temperature, moisture, and aeration. This is essential, since almost all the N in the soil is present in complex organic compounds not yet available for plants [72].
- Other nutrients (K, Ca, Mg, Fe, Mn). Besides C, N, P, and S, plants need other elements for normal growth and life cycles. Together with primary nutrients (N, P, and K), some are called secondary elements, such as K, Ca, and Mg, and other are micronutrients, like Fe and Mn. All these elements are essential for plant life, and their deficiency limits the productivity or may halt plant growth completely [73]
- Water holding capacity (WHC) and available holding capacity (AWC). Water in soil, held or available, depends on various factors, including plant cover type, plant density, growth stage, root depth, evaporation and transpiration rates, water infiltration amount, wetting rate, soil horizonation or layering nature, and the duration since the last rainfall or irrigation event. Measuring the quantity of water available for plant use influencing the likelihood of deep percolation proves beneficial in numerous agronomic scenarios [74].
- pH. It is a fundamental soil property that can significantly impact the availability and toxicity of elements, the activity of microbial groups, plant disease, the decomposition of natural and synthetic chemicals, and the microbial transformation of different atmospheric gases like CH_4 [68].
- Microbial biomass. It plays a crucial role in nutrient transformations and storage, such as the conversion of organic nitrogen into forms accessible to plants. Agricultural systems relying on internal nitrogen sources depend on microbial biomass and its activity to supply nitrogen to crops. The carbon within microbial biomass serves as stored energy for microbial processes, making microbial biomass carbon a potential indicator of microbial activity [75].
- Ratio of bacteria and fungi. Bacteria and fungi play a crucial role in nutrient cycling and the functioning of terrestrial ecosystems. The ratio of fungi to bacteria (F/B ratio) is employed as an index to examine the effects of environmental changes and human-induced disturbances on the structure and functionality of soil microbial communities [76].

- Coarse fragments. Coarse fragments in soil, also known as rock fragments or stones, can influence soil properties as bulk density, porosity, saturated hydraulic conductivity, and pore size distribution [77].
- Munsell color. This notation is a widely used system for describing and classifying soil colors. Soil color can indirectly reflect some aspects of soil properties, such as organic matter content and drainage conditions [78].
- Morphological aspects (slope and depth). Morphological indicators are probably the most common and simplest, with easily observed characteristics, yet are known for influencing other soil properties like nutrient concentrations [79].
- Humidity. Soil moisture, constituting one of the three phases in the soil system alongside soil minerals (solids) and air, is integral to various aspects of soil behavior. The mechanical properties of the soil, including consistency, compatibility, cracking, swelling, shrinkage, and density, depend on soil moisture content. Additionally, soil moisture plays a pivotal role in plant growth, the organization of natural ecosystems, and biodiversity. In the agricultural sector, ensuring the application of sufficient and timely moisture for irrigation, tailored to the soil–moisture–plant environment, is crucial for successful crop production [80].
- Corg/Norg. The carbon-to-nitrogen (C/N) ratio in soils describes the relationship between the concentration of C and N and is a sensitive indicator of soil quality, since it can assess carbon and nitrogen nutrient cycling in soils [81].
- $CaCO_3$. Calcium carbonate ($CaCO_3$) content in soil can significantly influence soil quality and properties, affecting mainly (and positively) pH value and with a positive role against clay dispersion [82].
- Surface and groundwater quality. Degradation of soil quality has repercussions for water quality. This is evident through the leaching of pesticides and excess nutrients into surface and groundwater, coupled with seawater intrusion into aquifers [83].
- Exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR). Soil salinity/sodicity is a key factor in evaluating soil quality, with particular influence on agricultural productivity and sustainability. In cases of extreme values, soil appears poor in physical properties, permeability, and vegetation presence. To access soil sodicity, exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) are normally used, with the possibility of linking the two with existing relationships in the literature [84].
- Texture. Soil texture refers to the relative proportions of sand, silt, and clay particles in a soil. This property plays a crucial role in influencing soil quality since it affects microbial activity, water content, soil temperature, aggregation, and porosity, together with gas exchange capacity, respiration of roots and microorganisms, and carbon storage capacity [85].

Table 5. Indicators for the sub-regional and local detection of soil quality with reference to soil properties.

Indicator	Data Available	Spatial Scale (MMU)
Electric conductivity	3D Soil Hydraulic database of Europe, from ESDAC database	Sub-regional scale (250 m)
	Maps of indicators of soil hydraulic properties for Europe, from ESDAC database	Sub-regional scale (unknown)
	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
Soil Organic Carbon, SOC	Organic Carbon (SOC) in European topsoils (EU25), from ESDAC database	Sub-regional scale (500 m)
	Pedologic Map at 250 K, from Lombardy Region Geoportal	Sub-regional scale (1:250,000)

Table 5. *Cont.*

Indicator	Data Available	Spatial Scale (MMU)
Bulk density in topsoil and subsoil	Map of topsoil physical properties for Europe, from ESDAC database	Sub-regional scale (500 m)
	Pedologic Map at 250 K, from Lombardy Region Geoportal	Sub-regional scale (1:250,000)
	LOSAN database by ERSAF	Punctual detention
Available P	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
	Phosphorus budget and P stocks, from ESDAC database	
Available N	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
Other nutrients as K, Ca, Mg, Fe, Mn	LOSAN database by ERSAF	Punctual detention
	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
	Map of heavy metals in the soil of the EU, from ESDAC database	Sub-regional scale (1000 m)
Water holding capacity and available water capacity	Map of topsoil physical properties for Europe, from ESDAC database	Sub-regional scale (500 m)
pH	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
	Pedologic Map at 250 K, from Lombardy Region Geoportal	Sub-regional scale (1:250,000)
	LOSAN database by ERSAF	Punctual detention
Microbial biomass	Map of soil microbial biomass and respiration, from ESDAC database	Sub-regional scale (1000 m)
Ratio of bacteria and fungi	Bacterial and fungal biomass (fatty acid methyl esters), from ESDAC database	Punctual detection
Coarse fragments	Pedologic Map at 250 K, from Lombardy Region Geoportal	Sub-regional scale (1:250,000)
	Geoenvironmental Cartography from the Province of Brescia Geoportal	Local scale (1:25,000)
Munsell color	LOSAN database by ERSAF	Punctual detention
Morphological aspects (slope and depth)	LOSAN database by ERSAF	Punctual detention
	Pedologic Map at 250K, from Lombardy Region Geoportal	Sub-regional scale (1:250,000)
	Atlas from the Province of Brescia Geoportal	Local scale (1:2000, 1:10,000, 1:50,000)
Humidity	Humidity, from Copernicus High Resolution Layers	Local scale (100 m)
Corg/Norg	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
$CaCO_3$	Map of chemical properties at the European scale, from ESDAC database	Sub-regional scale (500 m)
	LOSAN database by ERSAF	Punctual detention

Table 5. *Cont.*

Indicator	Data Available	Spatial Scale (MMU)
Surface and groundwater quality	Ecological and chemical status of surface waters, from ARPA Lombardy	Punctual detention
	LIM or LIMeco indices, from ARPA Lombardia	
	LTLeco index, from ARPA Lombardia	
	Chemical status of groundwater, from ARPA Lombardia	
ESP and SAR	LOSAN database by ERSAF	Punctual detention
Texture	Map of topsoil physical properties for Europe, from ESDAC database	Sub-regional scale (500 m)
	Pedologic Map at 250 K, from Lombardy Region Geoportal	Sub-regional scale (1:250,000)
	LOSAN database by ERSAF	Punctual detention

3.4.2. Soil Services

The following indicators for the quantification of the soil services (Table 6) have been primarily selected based on the methodology proposed in the previously cited Report Life + MGN, formalized in the research of Schikple et al., and on the categorization introduced by Bünemann et al. [22,41]; even if not strictly scientific material, for the present research, we also consulted the technical report of the Interactive Soil Quality Assessment, directly derived from Bünemann's study (Bünemann, E. K., et al. Concepts and Indicators of Soil Quality—A Review, www.iSQAPER-project.eu (accessed on 18 November 2023)). The indicators are biomass production; climate regulation; water quality, supply and regulation; aesthetic, cultural, and recreational value supply; biodiversity conservation.

Table 6. Indicators for the sub-regional and local detection of soil quality with reference to ecosystem services granted by soil.

Soil Services	Indicators	Data Available	Spatial Scale
Biomass production —forage production	Total amount of fodder produced	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
		Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Vegetation-oriented land use map of the Lombardy Region Geoportal	Local scale (1:10,000)
	Potential productivity	Land use and productivity from Geoenvironmental Cartography of the Geoportal of Brescia Province	Local scale (1: 25,000)
Climate regulation—carbon sequestration	Carbon dioxide stored/sequestrated in vegetation	Land use from DUSAF of Lombardy Region Geoportal	Local scale (10,000)
		Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Forest Map, both in Lombardy Region and in Brescia Province Geoportal	Local scale (1:10,000)

Table 6. *Cont.*

Soil Services	Indicators	Data Available	Spatial Scale
Water quality supply, regulation	Retention capacity	Forest Governance Map, from Lombardy Region Geoportal	Local scale (1:10,000)
		Forest types, from Forest Policy Plan form Brescia Province Geoportal	Local scale (1:10,000)
		Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
		Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
	Protective capacity	Data on water quality from the ecological and chemical state of surface waters by ARPA Lombardy	Punctual detention
		Data on water quality from the chemical state of groundwater by ARPA Lombardy	
		Data on water quality from LIM or LIMeco indices by ARPA Lombardy	
		Data on water quality from LTLeco index by ARPA Lombardy	
		Data on water quality from IBE index by ARPA Lombardy	
Aesthetic, cultural, recreational value supply	Landscape value	Sites of Community Interest, National and Regional Parks, Natural Parks, Priority Areas for Biodiversity in Protected Areas of the Geoportal of the Lombardy Region.	Local scale (1:10,000)
		Sites of the Natura 2000 Network in the Geoportal of the Lombardy Region	
		Regional Ecological Network in the Geoportal of the Lombardy Region	
		Provincial Ecological Network in the Geoportal of the Lombardy Region Monumental Trees in the Geoportal of the Lombardy Region	
		UNESCO Heritage in the Geoportal of the Lombardy Region	
		Information System for Landscape Assets (SIBA) reporting data and information on Biodiversity from the Regional Landscape Plan in the Geoportal of the Lombardy Region	
		Landscape Green Network in the Geoportal of the Province of Brescia	
		Survey of Landscape Protections and Assets in the Geoportal of the Province of Brescia	
		Landscape Constraints in the Geoportal of the Lombardy Region	
		Landscape Areas, Systems, and Elements in the Geoportal of the Province of Brescia	
		Naturalistic and Landscape Relevance in the Geoportal of the Lombardy Region	Local scale (1:25,000)
		Landscape Units in the Geoportal of the Province of Brescia	Local scale (1:50,000)
		Landscapes of the Insubrian Lakes in the Geoportal of the Province of Brescia	

Table 6. *Cont.*

Soil Services	Indicators	Data Available	Spatial Scale
	Recreational value and inspiration for culture, arts, educational and spiritual values, sense of identity	Historical Architectures (SIRBeC) in the Geoportal of the Lombardy Region	Local scale (1:10,000)
		Protected Architectures (MiBACT) or T.C.I. Reported Architectures in the Geoportal of the Lombardy Region Landscape Constraints in the Geoportal of the Lombardy Region	
		Naturalistic and Landscape Relevance in the Geoportal of the Lombardy Region	Local scale (1:25,000)
		Landscape from Constraints in the Geoportal of the Province of Brescia	Local scale (1:50,000)
Biodiversity conservation—agricultural and forest ecosystems	Common butterfly index	Some species geolocation available at the European Buffering Monitoring Scheme	Punctual detection
	Index of common avifauna in forest and agricultural habitat	Data produced as part of the MITO project, Agricultural Species, MITO2000	Punctual detection
	Percentage of agricultural land affected by landscape elements with high diversity	Land cover and land use from LUCAS European project	Sub-regional scale (2000 m)
	Standing and fallen deadwood	Data from the National Forest and Carbon Inventory INFC2015 Data from the Forest Map in the Geoportal of Lombardy Region	Punctual detection
	Forest connectivity	Discrete Classification Layer from Copernicus project	Local scale (100 m)
	Diversity of tree species	Data from the National Forest and Carbon Inventory INFC2015 Data from the Forest Map in the Geoportal of Lombardy Region	Punctual detection
	HNV farming	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
		Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Data on crop types, obtainable from the SiSco portal or from the Agricultural Use Map of the Geoportal of the Lombardy Region	Punctual detection
		Data about the presence of specific landscape elements, such as fountains, terraces, hedges, rows, from Protected areas of the Geoportal of the Lombardy Region or the Province of Brescia, Forest Boundaries from the Geoportal of the Lombardy Region and Areas, Systems and elements of the landscape of the Geoportal of the Province of Brescia	Local scale (1:10,000)

Indicators presented in Table 6 for different ecosystem services refer to a proper methodology for quantifying the service or to a proxy detection (resources already available and mappable). In summary, and with reference to the ecosystem service, the following indicators have been selected (the descriptions primarily refer to the calculation methodology):

- Total amount of fodder produced (Biomass production—forage production). As proposed by Schirpke et al., the quantification of this service can start from the grasslands and pastures distributed over the territory, to which average production values provided by ISTAT are associated [41]. The same approach can potentially be applied to any production type, including woody biomass, provided that appropriate statistical data are available.
- Potential productivity (Biomass production—forage production). Land supply service can also be evaluated in potential terms, considering these aspects. Such land characterization is provided by the Geoportal of Brescia Province.
- Carbon dioxide stored/sequestered in vegetation (Climate regulation—carbon sequestration). For service quantification, a useful source is the National Forest inventory related to land cover classes and converted to carbon. It is associated with INFC data on epigeal phytomass, root/shoot ratio, and current increase in epigeal tree volume per hectare, evaluated by forest categories, according to an adaptation of the method used in the National Carbon Accounting [86], based on the IPCC methodology [87].
- Retention capacity (Water quality, supply and regulation—discharge, infiltration, and flood control). As proposed by Morri et al., to quantify the service, one can use the retention coefficients typical of forest cover and management developed for the Marche Region, which provide volumes of water retained in the basin and thus subtracted from surface runoff. Information about forest management should be associated with these coefficients [88]. Alternatively, Nedkov and Burkhard [89] propose using retention rates for land cover classes, providing an estimate of volumes potentially retained during rainfall events. The coefficients need to be supplemented with vegetation cover information, such as the Forest Map of the Lombardy Region or, similarly, the DUSAF or Corine Land Cover.
- Protective capacity (Water quality, supply, and regulation—filtering capacity). A useful indicator is the protective capacity on surface and groundwater, geolocalized by the Lombardy Region. Water quality information at the hydrographic basin scale should also be considered for a complete characterization of the service.
- Landscape value (Aesthetic, cultural, recreational value supply). The Geoportals of Lombardy Region and Brescia Province provide a wide characterization of landscape features and elements in the territory, along with the geolocation of relevant sites from a naturalistic and ecological perspective.
- Recreational value and inspiration for culture, arts, educational and spiritual values, sense of identity (Aesthetic, cultural, recreational value supply). The Geoportals of Lombardy Region and Brescia Province offer extensive information on cultural and artistical features and elements in the territory. The opportunity for their use is considered an ecosystem service of the soil, providing support, survival, and value.
- Common butterfly index (Biodiversity conservation—agricultural and forest ecosystems). Butterflies play a significant ecological role, serving as vital pollinators, a source of sustenance for other species, and an index of ecosystem health. Butterflies not only play a key role in pollination, but are also sensitive to climate change, which impacts pollination patterns and habitat loss, making them highly responsive indicators. Consequently, a thriving population of butterflies often signifies a more robust and healthier ecosystem [90].
- Index of common avifauna in forest and agricultural habitat (Biodiversity conservation—agricultural and forest ecosystems). Birds are highly suitable for monitoring the effects of global environmental change due to their well-established history of global monitoring efforts. They are relatively easy to detect and identify, benefit from well-developed and cost-effective census methods, and our knowledge of the population biology, behavior, and life history is quite comprehensive (except in tropical regions), as pointed out by Xiao et al. [91]. Additionally, birds exhibit predictable population responses to environmental changes and are both widespread and diverse, with approximately 10,000 species found globally [91].

- Percentage of agricultural land affected by landscape elements with high diversity (Biodiversity conservation—agricultural and forest ecosystems). As underlined by Zarden et al., linear landscape features, such as ditches, hedgerows, rows of trees, and field margins, serve as crucial habitats and sources of ecosystem services, acting as ecological infrastructure for species within agricultural environments [92]. To enhance the representation of landscape composition in large-scale environmental evaluations at the regional level, it is essential to create spatial maps illustrating the distribution of these elements. In their research, Zarden et al. propose a methodology for modelling the spatial distribution of linear landscape elements, starting from LUCAS land use and land cover data [92].
- Standing and fallen deadwood (Biodiversity conservation—agricultural and forest ecosystems). As pointed out by Seidling et al., living trees and their decaying wood remnants together form the fundamental structural elements of forest ecosystems [93]. The arrangement of tree stands within a forest significantly influences species diversity. Multiple studies have demonstrated strong associations between the structural characteristics of tree stands and the diversity of fauna for various taxonomic groups and ecological guilds. Geolocation of these species can be obtained from the INFC database, combined with the Forest Map on the Geoportal of Lombardy Region.
- Forest connectivity (Biodiversity conservation—agricultural and forest ecosystems). As pointed out by Vogt et al., forest connectivity and, consequently, fragmentation significantly influence biodiversity, ecosystem services, and the mounting impact of human-driven land use changes [94]. Forest fragmentation can result in the isolation and depletion of species and genetic diversity, the deterioration of habitat quality, and a diminished capacity of the forest to support essential natural processes required for ecosystem well-being [94]. In their analysis, Vogt et al. present a methodology for the quantification of forest connectivity, for which Copernicus Discrete Classification data can be used [94].
- Diversity of tree species (Biodiversity indicators for agricultural and forest ecosystems). The diversity of tree species, and the prevalence of native species, is a well-recognized indicator of ecosystem health. Geolocation of these species can be obtained from the INFC database, combined with the Forest Map on the Geoportal of the Lombardy Region.
- HNV farming (Biodiversity indicators for agricultural and forest ecosystems). Proposed at the European level, it is composed of “3 sub-indicators that measure: the areas in which extensive agriculture is practiced and with a high proportion of semi-natural vegetation (e.g., meadows and pastures); areas with a mosaic of low-intensity agriculture (e.g., rice fields, olive groves, orchards) and natural, semi-natural and structural elements (e.g., hedges, dry stone walls, groves, rows, small watercourses, etc.) that contribute to the diversity of the agricultural landscape; agricultural areas that support rare species or a high richness of species of European or global interest” [48]. The methodology proposed for the Lombardy Region is based on an adaptation of the National Rural Network and develops the indicator with a very small reference cell, providing highly detailed results (cell size: 100 $\times$ 100 m) [67].

3.4.3. Soil Threats

Referring to Bünemann et al., Table 7 lists the remaining indicators, organized by soil threat. Among the various threats proposed in Bünemann’s research [22], only a few were selected due to data scarcity. Specifically, indicators related to erosion, contamination, sealing, biodiversity loss, and landslides and floods were chosen, excluding SOM decline, compaction, and salinization.

Table 7. Indicators for the sub-regional and local detection of soil quality with reference to soil threats and vulnerabilities.

Soil Threats		Indicators	Data Available	Spatial Scale
Contamination	Impacts	Heavy metal concentration, such as Cu, Hg, As, Cr, Cd, Pb, Mn, Sb, Co, Ni	Map of heavy metals in topsoils, from ESDAC database	Sub-regional scale (1000 m)
		Zn concentration	Zinc concentration in EU topsoils, from ESDAC database	Sub-regional scale (250 m)
	Effects	Contaminated areas	Contaminated and reclaimed sites, from Lombardy Region Geoportal	Punctual detention
	Vulnerabilities	Index of sensitivity to nutrient and pollutant inputs	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
Sealing	Impacts	Environmental pressures and sensitivities	Map 3.3 Environmental Pressures and Sensitivities of Brescia PTCP on the provincial Geoportal	Local scale (1:10.000)
	Effects	Landscape degradation	Map 2.4 Landscape Degradation Phenomena—Point Elements and Map 2.3 Landscape degradation phenomena—Areas at risk of widespread degradation, of Brescia PTCP on the provincial Geoportal	Local scale (1:10,000)
		Infrastructure fragmentation index	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Landscape compromise index	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Recovery time factor	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
	Vulnerabilities	Habitat standard per capita	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Matrix	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Overall naturalistic value index	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)
		Territorial biopotentiality	Land use from DUSAF of Lombardy Region Geoportal	Local scale (1:10,000)
			Land use from Corine Land Cover from Copernicus project	Local scale (100 m)

Table 7. *Cont.*

Soil Threats		Indicators	Data Available	Spatial Scale
Erosion	Impacts	Soil erosion processes	Multiple concurrent soil erosion processes from ESDAC database	Local scale (100 m)
			Slope, Length and Steepness factor from ESDAC database	Local scale (100 m)
			Soil erosion indicators for Italy from 1981 to 2080 by CMCC	Sub-regional scale (500 m)
	Sensitive management	Soil defense works	Soil defense works, from Lombardy Region Geoportal	Punctual detention
Biodiversity loss	Vulnerabilities	Biodiversity vulnerability	Potential threats to soil biodiversity in Europe by ESDAC	Sub-regional scale (500 m)
Landslides and floods	Impacts	Hydrogeological risk forecasts	Present and future climate data, from CMCC database	Sub-regional scale (varying)
	Vulnerabilities	Drainage area index (Idren)	Land use from DUSAF of Lombardy Region Geoportal	Local scale
			Land use from Corine Land Cover from Copernicus project	Local scale
		Landslide vulnerability	European Landslide Susceptibility Map (version2) by ESDAC database	Sub-regional scale (200 m)
		Characterization of particular vulnerable areas	Flood Directive, from Lombardy Region Geoportal	Local scale (1:10,000)
			Current PAI, from Lombardy Region Geoportal	
			Total hydrological risk (PRIM), from Lombardy Region Geoportal	
			Hydrogeological instability and hazard map from Lombardy Region Geoportal	
			Hydrogeology from Geoenvironmental Cartography from the Geoportal of the Province of Brescia	Local scale (1:25,000)
	Sensitive management	Strategic forested areas for landslide defense	Map 06 of Actions, from the Forest Steering Plan from the Geoportal of the Province of Brescia	Local scale (1:10,000)

It is worth mentioning that the distinction between soil services and soil threats is not always clear. For example, Bünemann et al. cite erosion as a soil threat and erosion control as a soil service. According to the European Environmental Agency, "spatial data about soil threats indicate focal areas for sensitive management and soil restauration" [38]. Therefore, erosion control interventions should be included in the threat categorization. Table 7 contains indicators about threat impacts and effects, as well as vulnerabilities and sensitive management actions towards them.

In summary, the following indicators have been selected:

- Heavy metal concentration (Contamination). Heavy metals adversely affect plant quality and yield and alter the size, composition, and activity of the microbial community, negatively impacting soil microbial properties such as respiration rate and enzyme activity, which are useful indicators of soil pollution [95].
- Zn concentration (Contamination). The balance of zinc (Zn) in soil, whether deficient or excessive, can affect soil functions and have repercussions for animal and human

health. Zinc is a micronutrient critical for various biological processes, and maintaining the right concentration is crucial for ecosystems' and organisms' well-being [96].

- Contaminated areas (Contamination). This involves locating contaminated sites with soil and/or groundwater pollution that have undergone a reclamation process and received certification of reclamation or permanent safety. The Geoportal of Lombardy Region maps such sites, including those with soil and groundwater contamination, sites with contamination of either soil or groundwater, sites with groundwater contamination and completed soil reclamation, and sites with completed reclamation awaiting certification.
- Index of sensitivity to nutrient and pollutant inputs (Contamination). This sensitivity, as conceptualized by the Lombardy Region in the Annex to the 7 May 2007 D.d.g. of the Lombardy Region [66], can be classified using average indices of plant associations essential for environmental unit structure. Units with a low nitrogen substrate are more sensitive than those with a high nitrogen substrate. In this light, specific parameters connecting land use and this sensitivity can be used, as presented in the cited Annex [66].
- Environmental pressures and sensitivities (Sealing). This information provides elements of territorial development and the anthropization processes that pose risks to environmental sensitivity elements. The Geoportal of the Province of Brescia provides an assessment of settlement pressure, particularly in Map 3.3 of the PTCP titled "Environmental Pressures and Sensitivities", which is a valuable resource for evaluating the impact of human development on environmental factors in the Brescia Province.
- Landscape degradation (Sealing). Landscape degradation, understood as the "deterioration" of landscape features, is caused by both abandonment-related processes, leading to a gradual loss of defining elements (including subsoil and surface degradation, vegetation, buildings, hydraulic structures, etc.), and by innovative interventions that introduce incongruous changes (in terms of size, shape, materials, usage, etc.) that do not align with the characteristics of the existing landscape, failing to achieve a satisfying reconfiguration of a new landscape–settlement framework. The Geoportal of the Province of Brescia reports this information and detects landscape degradation phenomena, both areal and punctual.
- Infrastructure fragmentation index (Sealing). As proposed in the 2021 Environmental Strategic Assessment of the Regional Lombard Plan [65], this index estimates the areas affected by fragmentation caused by infrastructure presence, but it can also be readily applied to the impact of other human activities. Calculating this indicator requires data on land use in the study area and the surface areas associated with various land use types, obtainable from sources like DUSAF or Corine Land Cover [65], along with a map of the infrastructure network, for example, from the Mobility Infrastructure layer of the Lombardy Region.
- Landscape compromise index (Sealing). Proposed in the 2021 Environmental Strategic Assessment of the Regional Lombard Plan [65], this index considers that transforming open spaces into built and urbanized areas creates residual areas that may suffer from degradation and underutilization. Widespread urbanization also leads to fragmentation, affecting the use of surrounding territory, ecosystem services, and environmental relationships. In this way, the proposed index evaluates both changes in settlement form, which deteriorates with an increase, and an overall occupancy index. These components are combined to provide an index of landscape compromise. Calculating this index requires data on land use in the study area and surface areas associated with various land use types, obtainable from sources like DUSAF or Corine Land Cover, [65], along with a map of the infrastructure network, which can be sourced from the Mobility Infrastructure layer of the Lombardy Region.
- Recovery time factor (Sealing). As proposed in the Annex to the 7 May 2007 D.d.g. of the Lombardy Region [66], recovery is evaluated in relation to the ecological value of environmental units damaged by human activities. The index is calculated on a

scale from 1 to 3, based on development times of over 30 years, between 30 and 100 years, and exceeding 100 years. Calculating this indicator requires, for the study area, data on land use and surface areas associated with different land use types, obtainable from sources like DUSAF or Corine Land Cover, along with the parameters specified in the cited Annex [66].

- Habitat standard per capita (Sealing). Defined by the 2021 Environmental Strategic Assessment of the Regional Plan of Lombardy Region [65], this concept assesses the ability of territories to support human functions, defining quantitative thresholds for evaluating the sustainability of anthropogenic pressures within a specific geographic area. Calculating this indicator requires, for the study area, data on land use and surface areas associated with various land uses, obtainable from sources like DUSAF or Corine Land Cover [65]. Additionally, it considers the population or equivalent inhabitants within the study area.
- Matrix (Sealing). Defined by the 2021 Environmental Strategic Assessment of the Regional Plan of Lombardy Region [65], the "Matrix" is determined by the type of element or recurring combinations of elements that are prevalent and interconnected in a landscape, influencing its structure and fundamental characteristics. For it to be recognized, these elements must make up at least 51% of the landscape coverage. A more stable environment, less susceptible to landscape disruption, is associated with a matrix value of at least 60%. This value represents the dominance of specific land use types, determined using data on land use and surface areas associated from sources like DUSAF or Corine Land Cover [65].
- Overall naturalistic value index (Sealing). Proposed in the Annex to the 7 May 2007 D.d.g. of the Lombardy Region [66], this index combines the degree of naturalness (N), the state of danger and rarity (P), and the potential for temporal and spatial restoration (R). The indicator is obtained by estimating the components N, P, and R and assigning a value from 0 to 10, with the maximum value being the overall index value for the examined environmental unit. Calculating this indicator requires data on land use in the study area and surface areas associated with different land use types, obtainable from sources like DUSAF or Corine Land Cover, along with the parameters specified in the Annex to the 7 May 2007 D.d.g. of the Lombardy Region [66].
- Territorial biopotentiality (Sealing). Defined by the 2021 Environmental Strategic Assessment of the Regional Plan of Lombardy Region [65], this indicator, among other outcomes, provides information about the degree of stability, evolutionary trends, effects of potential transformations, and biological deficit introduced by transformations or environmental resource depletion in the study areas. Calculating this indicator requires data on land use in the study area and the surface areas associated with different land use types, obtainable from sources like DUSAF or Corine Land Cover [65]. Additionally, parameters characterizing territorial biopotentiality (possibly referring to specific environmental parameters) for each type of land use are required, and these can be found in the technical documentation of the indicator within the 2021 Environmental Strategic Assessment of the Regional Plan of Lombardy Region [65].
- Soil erosion processes (Erosion). Soil erosion threatens agriculture and the natural environment and is caused by factors such as water, wind, and morphological aspects. Evaluating indicators of soil erosion is crucial, especially in the context of climate change, thus in future scenarios. A prior reference for the indicator is represented by the ESDAC database with data sources at different scales, together with erosion indicators for Italy by CMCC.
- Soil defense works (Erosion). The Soil Defense Works Information Service (ODS) provides an up-to-date picture of the maintenance and securing of slopes and watercourses to mitigate hydraulic and hydrogeological risk in Lombardy. The Geoportal of Lombardy Region provides this resource.
- Biodiversity vulnerability (Biodiversity loss). The effect of biodiversity loss can be computed by combining the effects of different data inputs over the territory, such as

soil erosion, climate change, habitat fragmentation, salinity, and compaction. Potential threats are mapped by ESDAC.

- Hydrogeological risk forecasts (Landslides and floods). Reliable forecasts about climatic conditions and their changes in the coming years are essential in the climate change era. A valuable source of data forecasts is the Euro-Mediterranean Centre of Climate Change.
- Drainage area index (Landslides and floods). Defined by the 2021 Environmental Strategic Assessment of the Regional Plan of Lombardy Region [65], the Idren index is the ratio between the draining surface and the total surface area of each domain, representing the percentage of non-impermeable soil. The index determines the effects of urbanization on soil permeability, in terms of anthropogenic pressure. Calculating this index requires data on land use in the study area and the surface areas associated with different land use types, obtainable from sources like DUSAF or Corine Land Cover. Additionally, you would require coefficients for the draining surface for each type of land cover, which can be found in the 2021 Environmental Strategic Assessment of the Regional Plan of Lombardy Region [65].
- Landslide vulnerability (Landslides and floods). This evaluates the spatial probability of generic landslide occurrence, considering factors such as elevation, lithology, climatic conditions, and land cover [97]. ESDAC provides valuable resources in this direction.
- Characterization of particular vulnerable areas (Landslides and floods). Geolocating areas particularly subject to hydrological risk is essential, especially for their position. Various sources in the regional and provincial Geoportals provide this service.
- Strategic forested areas for landslide defense (Landslides and floods). As reported by Forbes and Keith, forests and trees play a significant role in preventing landslide, confirmed by various scientific studies and with different contributions. For instance, deep-rooted plants help reduce soil moisture through transpiration, lowering the risk of landslides, and forests can act as a barrier against smaller debris flows and rock falls, mitigating their impact and blocking their progress [98]. An interesting data source in this direction can be found in the Geoportal of Brescia Province.

4. Discussion

The research involves the selection of eleven datasets: four at the EU level, two at NUT0, four at the NUT2, and one at the NUT3. For the Brescia Province case study, 55 indicators are proposed, comprising 19 related to soil properties, 15 on soil services, and 21 addressing soil threats.

As already highlighted above, the purpose of the analysis was to verify the possibility of building a framework of soil quality indicators that would allow, for the case study of the Province of Brescia, a homogeneous coverage from the point of view of spatial planning. At the scale of interest, the objective limitation was being able to refer only to open-source data. Environmental processes are scale-dependent, where the term scale refers both to the geographic coverage and to the amount of details mapped [99], namely to the extent and to the resolution. When the resolution is high, the results are more accurate, since the observed variables are closer to the individual parcel level at which the spatial development process is affected by local choices [100]. Consequently, we can assume that local coverages require local resolutions, regardless of the associated costs [101]. On the other hand, coarser resolutions lose many details, but are used for higher coverages and thus for a wide-area vision. Furthermore, high-resolution scales can be used for large coverages if the data are available for the entire zone [102]. The case study demonstrates the feasibility of using finer-resolution data for the local scale and coarser data for supra-local scales. In this context, an indicative threshold for distinguishing finer resolution from coarser resolution is set at 250 m for rasters and 1:25,000 for vectors. Regarding the consideration of point detections, the information could be interpolated to achieve homogenous coverage throughout the territory. However, the resolution obtained from such interpolation depends on calibration choices, which are left to expert intervention.

The temporal representativeness of the indicators is a complementary issue, strategically important for constructing at least two temporal thresholds of comparison, which allow for more targeted and informed planning of interventions. Since spatial planners rely on open data, updating these datasets is independent of researchers' need. Additionally, the frequency of data updates is a relevant issue, but it is not controllable by planners. However, the growing awareness of soil quality importance (as highlighted in Section 1), reinforced by new legislative proposals in the European context (such as the Soil Monitoring Law), is expected to drive improvements in data updating.

The objective of monitoring soil quality at the scale of spatial planning remains an open theme that requires an interdisciplinary approach. In particular, the research highlights existing datasets for a holistic characterization of soil quality, emphasizing their usability in both the European context and the proposed case study. While the research gap is addressed from the spatial planning perspective, a truly holistic vision necessitates the integration of diverse competences. Starting from already existing best practices (see Section 5), new frameworks need to be built, especially for the spatial context of interest. These frameworks must be implemented primarily with the support of soil scientists and agronomists, and they should then involve geomatics and remote sensing. This is a particularly strategic topic in light of the monitoring requests that come from European legislative proposals.

The comprehensive effort invested in classifying indicators based on soil properties, services, and threats facilitates the creation of a flexible characterization of soil quality. This flexibility ensures adaptability to various territorial, social, and economic contexts, as well as diverse planning priorities. More precisely, the soil property indicators provide insights into the features that make a specific soil suitable for different uses, especially in agronomic terms, highlighting its potentialities and strengths. Under the supervision of agronomists, soil scientists, and other field experts, maps detailing a specific soil property or suitability can be created and employed as tools for assessing soil health and its adaptability to various uses. For instance, these maps can inform decisions on different crops that may be cultivated based on a comprehensive physical, chemical, hydraulic, and fertility characterization. This becomes a planning matter, especially in contexts with valuable agriculture that play a crucial role in sustainable development. A thorough characterization of soil properties, including soil suitability, provides valuable guidelines for planning aimed at preserving the territorial economy and its distinctive features. On the flip side, the characterization of soil services, representing the intersection of human activities and the environment, delineates the capabilities of non-urbanized soil as a resource. This type of soil evaluation supports the concept of land planning that is both flexible and tailored to local needs and peculiarities, while also being open and responsive to global challenges such as climate change and biodiversity loss. Indicators of soil threats can guide a strategic and resilient land planning process, emphasizing the pivotal role of soil preservation within a specific spatial context. This approach is particularly crucial for addressing existing threats, both natural and anthropogenic, vulnerabilities, and historical settlement patterns. Consider, for instance, landscapes already compromised by settlement patterns; in such cases, planning that recognizes the link between soil conservation and landscape protection can make a significant difference.

5. Conclusions

As mentioned earlier, while there is not an established reference framework for sub-regional soil quality detection in spatial planning, there are existing best practices for similar characterizations. For example, in Emilia Romagna, efforts to assess soil quality across the territory led to the creation of the Synthetic Soil Quality Index Map (500 m $\times$ 500 m) as part of the SOS4LIFE project. This initiative, conducted in collaboration with CNR researchers and the Emilia-Romagna Region, resulted in output maps that provide a summarized index of soil quality (divided into five levels) for each part of the territory. These indices take into account the quality and quantity of ecosystem services present [34].

The limitation of methodological Phase 3 lies in its reliance on administrative borders, which may not adequately capture the heterogeneity of territories like Brescia Province. Factors such as agricultural and naturalistic characteristics, fragmentation levels, functional diversity, and morphological traits [103] require more precise delineation. To address this limitation and achieve a more accurate cartographic characterization tailored to homogeneous areas, a further downscaling approach is necessary. This involves selecting specific indicators that closely align with the characteristics of these sub-regions.

For example, in the case of Brescia Province, a sub-region classification is feasible using Homogeneous Territorial Areas (Ambiti Territoriali Omomogenei—ATO) defined in accordance with Regional Law 31/14 (Regional Law 28 November 2014, n. 31. Disposizioni per la riduzione del consumo di suolo e per la riqualificazione del suolo degradato. Regulations for the reduction of land consumption and redevelopment of degraded land. Lombardy Region, art. 2.), and depicted in Figure 6, as "characterized by relational areas, homogeneous socio-economic, historical and cultural characters, adequate to allow the implementation of the contents of R.L. 31/14 and more generally, the development of policies and implementation of projects capable of integrating issues related to landscape, environment, infrastructure and settlements". In the same document, the ATOs of Brescia Province are defined as comprising six distinct areas (see Figure 6), varying in size but averaging about 23 km^2 and encompassing around 35 municipalities each. In ATOs primarily dedicated to agriculture, especially for high-value wine and oil crops, indicators related to agronomic and soil aspects gain particular relevance. These may include nutrient characterization, pH levels, and organic matter in the soil. Additionally, indicators with a naturalistic value, such as HVN (High Nature Value) farming, are likely to be more pertinent in these specific territorial contexts. Emphasizing these indicators provides a focused and meaningful perspective on agricultural practices and their influence on soil quality within these areas. The undeniable touristic and landscape value of territories is a crucial consideration. Within this context, there is a strong emphasis on tailoring recommendations for reducing land consumption to fit the specific characteristics of each territory. This involves identifying areas where dispersion and fragmentation phenomena are more pronounced [63], underscoring the imperative for implementing effective containment measures. This approach recognizes the uniqueness of each area and emphasizes the strategic measures required to preserve its distinctiveness and safeguard its touristic and landscape appeal. Indicators associated with landscape vulnerability and sensitivity, infrastructural fragmentation index, and landscape impairment index (e.g., [65]) play a pivotal role in assessing and mitigating the impact of development on the landscape. These indicators serve as essential tools for guiding actions and policies aimed at preserving the unique qualities of the landscape. They ensure that development activities are conducted in a manner that respects and sustains the natural and aesthetic attributes of the environment.

Additionally, it is noteworthy to discuss the limitations of institutional datasets such as Geoportals, which could greatly benefit from upgrading their map systems. This upgrade should not only focus on updating time frames but also expanding the diversity of indicators mapped across the territory. Specifically, NUT3 Geoportals often lack a mapping of what has been referred to here as soil property indicators, which are, however, available at an appropriate spatial scale in the European database ESDAC for sub-regional planning. As demonstrated in this work, there is a pressing need to integrate the proposed soil quality assessment methodologies and, more crucially, the available data. This integration is necessary to establish a unified and effective system for data classification and visualization.

An apparent weakness in the research lies in the current inability to directly implement the method for sub-regional or local planning. As discussed in previous sections, it is imperative for sub-regional authorities to undertake a thorough selection of the most relevant indicators, create synthetic indices with expert support, both from the specific research fields and the practitioners, adapt indicators to homogeneous territorial contexts, and ultimately establish a unified institutional database that is both adequate and user-friendly for efficient data retrieval.

A notable strength of the research lies in its capability to create precise maps depicting soil characteristics using open-source and well-defined indicators, even at sub-regional scales. The effective downscaling of soil-related issues is crucial for preventing soil consumption and degradation, aligning with site-specific features and planning policies [104,105]. This ability enhances the precision and applicability of the research findings in addressing local concerns and supporting sustainable land management practices.

The presented list of indicators is valuable, primarily for supporting sub-regional planning, with subsequent applicability to local planning. Its aim is to formalize a comprehensive framework for detecting soil quality across the territory. The proposal is expansive and diverse, striving to advocate for a soil quality characterization that extends beyond pedological aspects to encompass broader and more comprehensive considerations. This includes factors related to naturalistic, cultural, and landscape preservation. Additionally, the proposal highlights the availability of essential sub-regional data for evaluating soil quality.

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