Soil Security 10 (2023) 100086

Contents lists available at ScienceDirect

Soil Security

journal homepage: www.sciencedirect.com/journal/soil-security

A proposal for the assessment of soil security: Soil functions, soil services and threats to soil

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ARTICLE INFO

Keywords:
Capacity
Condition
Capability
Capital
Connectivity
Codification
Utility
Soil health
Soil quality

ABSTRACT

Human societies face six existential challenges to their sustainable development. These challenges have been previously addressed by a myriad of concepts such as soil conservation, soil quality, and soil health. Yet, of these, only soil security attempts to integrate the six existential challenges concurrently through the five biophysical and socio-economic dimensions of capacity, condition, capital, connectivity and codification. In this paper, we highlight past and existing concepts, and make a proposal for a provisional assessment of soil security. The proposal addresses three roles of soil: soil functions, soil services and threats to soil. For each identified role, we indicate a potential, but not exhaustive, list of indicators that characterise the five dimensions of soil security. We also raise issues of quantification and combination of indicators briefly. We found that capacity and condition are theoretically easier to measure and quantify than connectivity and codification. The dimension capital might be conveniently assessed using indicators that relate to the economic value of soils. The next step is to test this proposal for which we make recommendations on potential study cases and examples. We conclude that the five dimensions of soil security can potentially be assessed quantitatively and comprehensively using indicators that characterise each role, but also found that there is need for further work to devise an operational measurement methodology to estimate connectivity of people to soil.

1. Introduction

Human societies face seven existential challenges to their sustainable development, namely, Food, Water and Energy security, Climate Change Abatement, Biodiversity Protection Ecosystem Services Delivery and Human Health. The challenges have something in common: they are global, interrelated and usually difficult to address. Soils play a key role in all these challenges through the provision of food, water, biodiversity and support for ecosystem services. They too, however, are under pressure of a growing world population and sustained human impacts upon the planet (Amundson et al., 2015).

Ideas of soil utility began around agricultural capability and broadened to ideas around what soil can do. These ideas are reflected in the concept of ecosystem services. The ecosystem service approach, first recognised in the early 1980′s (Braat and de Groot, 2012; Ehrlich and Ehrlich, 1981; Mooney and Ehrlich, 1997), has since developed into a framework which measured value via '*supporting, provisioning, regulating* and *cultural*' services (Schwilch et al., 2016). Most commonly, soil is referred to as provider of a significant '*supporting*' service recognised as natural capital, estimated by its inherent and manageable soil properties, and enabled by its ongoing soil forming processes. This supporting service can be degraded and lost when exposed to soil degradation processes (Dominati et al., 2014) such as erosion, salinisation, decline in biodiversity. Of the three other services, '*provisioning*' is delivered by soil through biomass production and the provision of raw materials for humans and animal to build infrastructure. The ability of soil to provide nutrients, remediate/store contaminants, mitigate floods, store carbon, recycle waste and regulate pest and disease contribute to its '*regulating*' service. Soil also provides '*cultural*' services enabling recreation and sustain aesthetics, heritage and cultural values (Dominati et al., 2014; McBratney et al., 2017b).

The delivery of these services is linked to the soil's ability to provide a suite of functions. There have been a number of definitions of soil functions and organisations into categories (Baveye et al., 2016; Blum, 2005; Commission of the European Communities, 2006; McBratney et al., 2012).

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https://doi.org/10.1016/j.soisec.2023.100086
Received 14 July 2022; Received in revised form 15 December 2022; Accepted 23 January 2023
Available online 25 January 2023

Essentially, soil functions are defined as "*bundles of soil processes that underpin the delivery of ecosystem services*" (Bünemann et al., 2018; Kopittke et al., 2022). Over time, the literature identifies several soil functions which are commonly recognised, namely: biomass production, nutrient cycling, water cycling, carbon storage and cycling, protecting biodiversity, providing recreation, store of history and the provision of building materials. The recognition that soil provides these functions and supports these services has recently introduced the idea of soil being multifunctional, soil does many things simultaneously (Kopittke et al., 2022). Historically, the focus has largely been on the soil's ability to provide food, fibre and biomass for energy, but recently it has been recognised that this focus and management of soil for this one function comes at the expense of others, decreasing its ability to provide the other functions critical to planetary health (Kopittke et al., 2022) and in extreme cases lead to catastrophic degradation related to soil threats, including erosion, acidification, salinisation, and structural decline.

These changing foci over time has led to the development of a myriad of concepts that recognise that soil degradation can have an impact on agricultural productivity and ecosystem services: examples are soil conservation, soil quality, soil health, soil protection and soil security. They all attempt to put soil at the centre of the problem and do justice towards the need to maintain and manage the soil condition, yet perhaps only the concept of soil security has been advocated as anchored to the societal challenges faced by humanity.

Soil security has been defined as the maintenance and improvement of the world's soil resource to produce food, fibre and fresh water, contribute to energy and climate sustainability and maintain the biodiversity and the overall protection of the ecosystem (Koch et al., 2013). This involves maintaining and optimising soil's structure and form; diversity of organisms; nutrient cycling capacity; ability to act as a substrate for plant growth; ability to regulate, store and filter fresh water; and capacity to sequester carbon dioxide from the atmosphere. In order to secure soil, we need to be able to assess both its current state and optimal biophysical state (McBratney et al., 2014). These are soil condition and capacity, respectively. Together, they constitute soil capability. A soil's capability may change over time, primarily through a change in condition. Further, in order to determine the suitability of a soil for a particular purpose, we must also be able to assess the value placed on the soil by society, the actors who influence its use and how the use is regulated. These value-laden criteria are, respectively, capital, connectivity, and codification.

Soil security address conceptually the existential challenges outlined above in a systematic way, thus aiming at resolving overlaps between the existing concepts spanning soil research. To date, however, the literature lacks a quantitative framework which can relate the dimensions of soil security to indicators, functions, services and threats to soils. The aims of this paper are therefore:

1 To highlight the past and present concepts related to soil security.
2 To identify concepts that are useful to assess soil security comprehensively and quantitatively.
3 To use the concepts identified as useful and propose a nascent provisional framework to assess soil security.

2. Past and existing concepts of soil value and care

Beginning in the early- to mid- twentieth century, concepts have arisen to define how society values and cares for soil. These have been described by McBratney et al. (2017a) and is summarised in Box 1 of Supplementary Material.

A large number of concepts have been developed over the years to describe and define the idea of valuing soils. According to Robinson et al. (2012), soil quality, health and change are recently developed, emerging and evolving conceptual frameworks. The terms soil health and soil quality have been used by many almost interchangeably, to mean "*fitness to support crop growth without becoming degraded or otherwise harming the environment*" (Karlen et al., 1997, p.6), which also equate soil health with dynamic, as opposed to inherent, soil quality. Doran (2002) also used the terms interchangeably, referring to "*soil quality or health*" (p. 121). According to Robinson et al. (2012), soil quality is a measure of soil natural capital, and soil change recognises that soil natural capital is not a fixed quantity. In a recent publication by the EEA, soil health assessment was linked to threshold of threat value, which in turn depend on the soil condition. In order to meet the global existential challenges described above, we recognise the need of a broader concept that encompasses the economic, social and policy aspects of soil, which is clearly defined, and enables us to measure and quantify the degree to which soil is being valued and cared for. It is also important that this broader concept recognises the place of earlier concepts of caring for soil. Some concepts inevitably overlap.

Fig. 1 shows the location of the various prior concepts in relation to soil functions, soil services and threats to soil and the five soil security dimensions of soil security: capability, condition, capital, connectivity, and codification. Many of the concepts described above are relatively narrow in scope, generally focusing on biophysical attributes of soil (condition and capacity dimension). Few concepts span several dimensions, and many of them overlap one with another. The soil security concept covers the entire space.

3. Processes, functions, services and threats

The use of the terms soil processes, functions, services and threats are ubiquitous in the literature, often interchanged but not clearly defined (Baveye et al., 2016). This lack of clarity may reflect the field of research, for example processes and functions are commonly used by the soil science community, whereas services are used in the disciplines of ecological or environmental economics. A distinction between properties along with processes and functions needs to be addressed to improve communication across these disciplines, which all contribute to understanding soil security. We recognise that soils:

1 result from a clearly defined set of soil forming (pedological) processes, and
2 these contribute to regulating processes assembled as functions, and that
3 these functions can be impacted by particular degradation processes which are labelled soil threats.

This will provide a conceptual framework to make the distinction between soil processes, functions and services that can be described, evaluated and monitored using soil properties and/or functions.

The soil-forming factors result in unique patterns of soil that reflect the local effects of climate, organisms, relief, parent materials, and time. Fig. 2 shows a series of processes affecting soils, which vary in space and time according to soil-forming factors. A suite of pedological processes have been recognised, including the addition, transformation, translocation and losses from a soil. However, natural processes, land use change and human induced management will impact on the soil change and soil processes (Yaalon and Yaron, 1966). While these changes are reflected in the soils' observed properties or attributes (often measured as masses, volumes or rates), these evaluations are made using indicators based on criteria that reflect values or utility judgements. The translation of properties to indicators is used to assess the soil functions and threats to soil that occur with or without direct human intervention.

4. One size does not fit all: absolute vs relativistic (genosoils vs phenosoils) assessment

4.1. Soil function potential

Soil functions and soil-based ecosystem services are often evaluated in absolute terms according to the fulfilment of some conditions or the

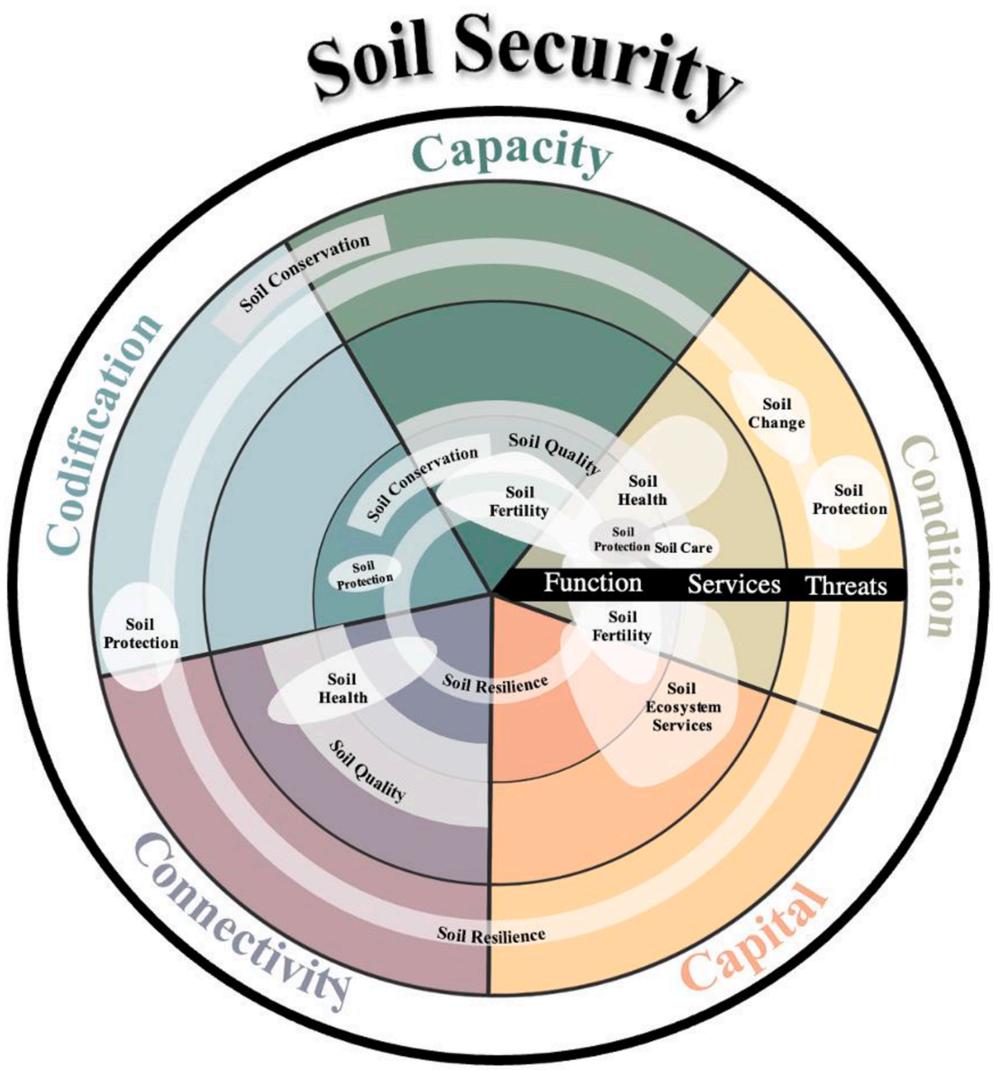

Fig. 1. Scope of existing soil value and utility concepts in relation to roles and dimensions. The white shaded areas illustrate the range of dimensions and roles which each concept is perceived to cover and do not indicate the relative importance of the terms. The soil security concept attempts to cover the whole space.

distribution of indicator values within a study area (*can this soil perform X function satisfactorily?*) (Rabot et al., 2022; van der Plas et al., 2016). It is rare to see soil functions being evaluated with respect to the individual soil intrinsic potential (*to which degree is this soil performing X function given its capacity?*) (Vogel et al., 2019). Vogel et al. (2019) defined the intrinsic potential of a soil as "*the maximum a soil can offer based on its inherent properties with respect to various individual soil functions*" and is captured by the capacity dimension in the soil security framework. Quantifying the soil function potential considering the constraints of the soil's inherent properties (i.e. slowly evolving or resulting from long-term pedogenetic processes like particle-size distribution), site conditions (e.g. climate, relief), while assuming optimal condition of more dynamic properties which can be modified by management (related to soil condition) (Vogel et al., 2019), may set feasible management targets without other socio-economic limitations. On the contrary, assessing the soil potential independently of soil properties (Bouma et al., 2017) may set targets that are too ambitious for the pedological setting. The fulfilment of the soil function relative to its potential is calculated as the ratio (or difference) between the current function performance and the soil function potential (based on measurements of the indicators). Within the soil security framework, this would for example correspond to the ratio of condition to capacity for a particular soil function.

4.2. The quest for the ideal soil

An absolute assessment of soil functions is made against an '*ideal*' soil, but therein lies the problem '*what defines ideal?*'. This can be done in several ways. One being the characteristics of our most productive or resilient soil. Often, this is seen as some kind of mollisol or chernozem. However, this primacy is probably only really defined for the function biomass production and not necessarily for other functions, such as preservation of cultural heritage. A second way of defining ideal is to back propagate a mathematical relationship between soil properties and the maximum expression of a soil function. For example, on the average, biomass production is maximised around pH 6.5–7 and drops off above and below those figures, but it may well be that biomass production will be maximised at varying pHs (sometimes outside the 6.5–7 range) depending on the particular soil via a whole suite of interacting characteristics.

The concept of a reference state or condition is widely established for assessing the ecological condition of freshwater ecosystems (Stoddard et al., 2006), but this is currently not the case for soil systems. The comparison of current soil functions with a reference state often relies on chronosequences. For example, Teixeira et al. (2020) investigated the variation of soil functions along a secondary forest succession, taking recently abandoned agricultural plots and primary forest as the starting

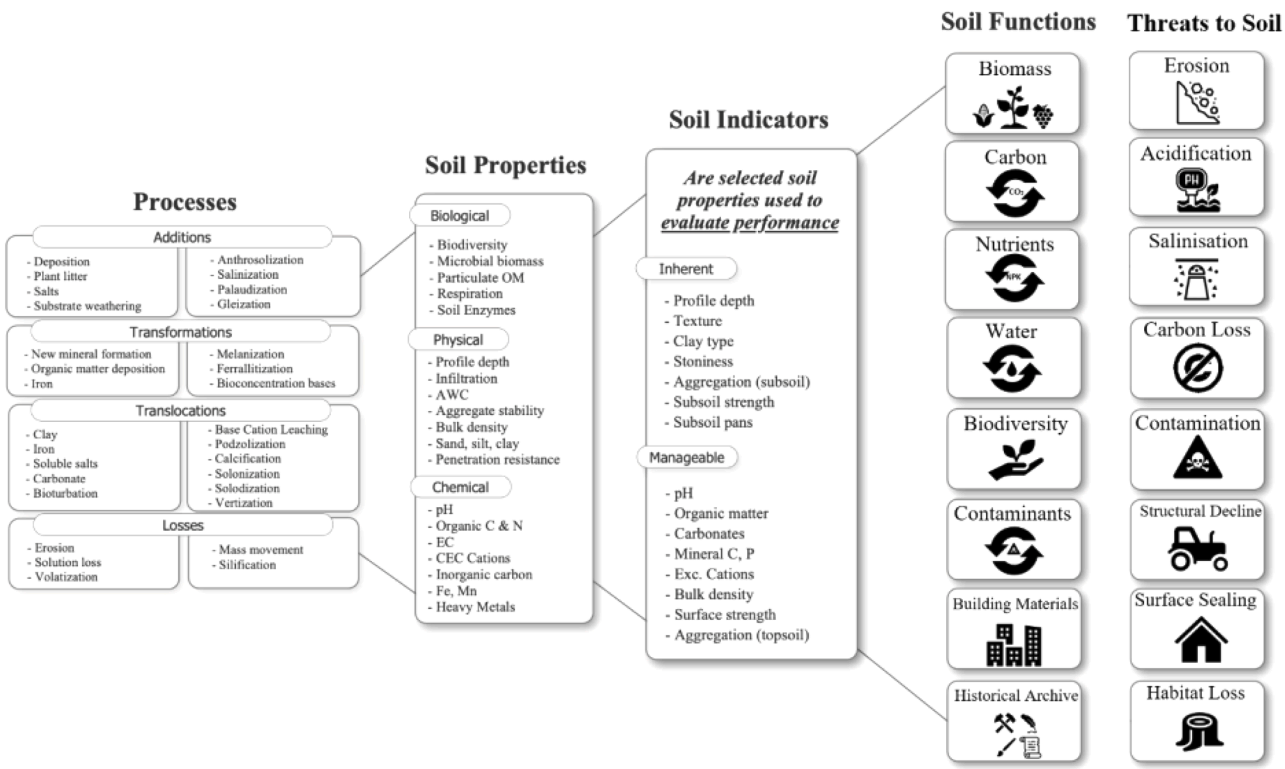

Fig. 2. An illustration of the relationship between the dominant soil process affecting soil formation and the soil properties that are used to describe the soil itself. The translation from soil properties to equivalent soil indictors is based in value judgements that in-turn are used to evaluate if a soil has the capacity and condition to perform a soil function, i.e. its capability. Capability = Capacity + Condition.

point and reference respectively. These reference states, however, are defined for local conditions and not in absolute terms. In the case that we could specify a reference soil system that represents a *secure soil*, distance-based methods could be applied to integrate several indicators into an overall similarity/dissimilarity integrative index (Legendre and Legendre, 2012), an approach proposed for environmental assessment (Tran et al., 2019).

4.3. Genosoil vs phenosoil assessment

Soil functions are context-dependant in time and space (Hoffland et al., 2020) according to the soil inherent properties, climate conditions and land use. Droogers and Bouma (1997) and later Rossiter and Bouma (2018) acknowledged the effects that current and past management can have on soil functions and capability with the concepts of genoform or genosoil (Huang et al., 2018) (i.e., genetic soil type or dominant soil class in a detailed soil map at the level of soil series or equivalent) and phenoform or phenosoil (i.e., permanent variant of the genoform, physico-chemical properties as a result of soil management with a substantial effect on soil functions). In the relative approach, we can take a soil in its '*natural*' or pristine condition and measure its ability to function, provide services or mitigate threats. We can then compare in a relative way this soil with a soil of interest with similar pedogenesis which may have a different land use history. The relative approach probably requires more information and soil understanding (because it recognises many kinds of soil) and is likely to produce assessments which are more suitable for guiding stewardship, particularly if remediation or regeneration is required.

5. Approaches to quantification

In the soil science literature, there are multiple approaches for assessing and quantifying soil functions and soil-based ecosystem services (e.g. Calzolari et al. (2016)) and potential threats to soils (e.g. Orgiazzi et al. (2016); Troldborg et al. (2013)). Greiner et al. (2017) divided the quantification approaches of soil functions into three groups:

1 Indicator approaches,
2 Static approaches,
3 Dynamic approaches.

Within each of these approaches, the assessment of soil functions and soil-based ecosystem services can be done for a set of locations or mapped across a region. Indicator approaches estimate soil functions using one-dimensional proxies (i.e. a single soil property). Static approaches apply simplified empirical rules to quantify the *general capacity of a soil to perform a function*, without considering land use or management (Greiner et al., 2017). Dynamic approaches comprise environmental and biophysical models that characterise soil processes and account for spatial and temporal changes in land use, management, and environmental conditions. Alternatively, we also distinguish between simplified empirical models and process-based dynamic models to quantify soil functions.

Similarly, the numerous frameworks for assessing threats to soil also range from mapping indicators, knowledge-based approaches, to empirical or process-based models that can incorporate multiple scenarios of climate, land use change, and management (van den Akker and Hoogland, 2011). These approaches can present the assessment of several soil functions, soil-based ecosystem services, or threats to soil individually, or these can be integrated into a composite index. For example, Gardi et al. (2013) quantified and mapped a composite index of the potential threats to soil biodiversity at the scale of Europe. They aggregated seven indicators of relevant pressures based on weights assigned by a panel of experts.

We aim to develop composite indices for assessing the different dimensions of soil security, and we will therefore explain integrative approaches with more details. General steps for quantification of composite indices of soil functions, services or threats to soil involve (Andrews et al., 2002a, 2002b):

1 Selection of a minimum dataset (MDS) of indicators,
2 Transformation of indicator values into unitless scores,
3 Integration of scores into composite indices.

5.1. Selection of minimum dataset of indicators

Indicators are characteristics that can be correlated, or are thought to be correlated with soil functions, services and threats of interest. These characteristics were sometimes referred as '*indicator variables*', '*indicators*', '*metrics*', '*surrogates*' and '*proxies*'. The existing body of literature on physico-chemical and biological soil attributes and environmental conditions used as indicators of soil functions is practically boundless. Some reviews explain in detail the suitability of a soil attribute or set of related properties as indicator of soil quality and soil functions (e.g. soil structure (Rabot et al., 2018), soil organic carbon (Liptzin et al., 2022; Vogel et al., 2019), soil organic matter (Hoffland et al., 2020)) given their relationships with other soil properties and key role supporting the soil processes. In the field of soil ecology, ecosystem functions are often characterised via a quantitative assessment of functional genes related to nutrient cycling and enzyme activity (Chen et al., 2020). For a list of potential indicators of soil quality and of soil functions we refer to the comprehensive reviews by Schoenholtz et al. (2000), Stone et al. (2016), Greiner et al. (2017), van Leeuwen et al. (2017), and Bünemann et al. (2018).

Multiple criteria have been proposed for the selection of potential indicators (Doran and Zeiss, 2000; Schoenholtz et al., 2000): 1. the indicators should be easy measure or possible to estimate with pedotransfer functions, 2. inexpensive, 3. sensitive to variations in management, 4. relevant across sites or over time, 5. useful and comprehensible for different stakeholders, 6. helpful in revealing ecosystem processes, 7. rationally linked to the soil function and easily interpretable, for example, if it is difficult to distinguish whether the value of an indicator means better or worse performance it should be discarded (Llovet et al., 2021).

The soil properties included in the minimum dataset (MDS) vary according to the soil functions being assessed and the land use (e.g., soil remediation projects, Volchko et al. (2014)). Indicators can be direct measurements or estimated with pedotransfer functions or mechanistic models (Greiner et al., 2017).

From the list of potential indicators, there are several methods to select the MDS, which are not mutually exclusive, including: literature review, expert knowledge and stakeholder perceptions, "*logical sieve*", or statistical methods for dimension reduction. In the "logical sieve" (Ritz et al., 2009; Stone et al., 2016), a preliminary selection of potential indicators from the literature is scored by stakeholders and experts based on scientific and technical criteria. The scores are then used to rank and prioritise the final indicators. Alternatively, when the purpose is to assess the effect of a management treatment on soil functions, statistical analysis (e.g. analysis of variance (ANOVA)) can be used for identifying which indicators are more sensitive to management (Llovet et al., 2021). Dimension reduction or ordination analyses (e.g. Principal Components Analysis (PCA)) are often applied for selecting the variables explaining most of the variability of the dataset and for eliminating redundant information (Andrews et al., 2002a).

5.2. Transformation of indicator values into unitless scores

The next step in the assessment is to transform the indicators of soil functions, services or threats to soil into an ordinal scale or unitless scores. The transformation from indicator values to scores can be through linear or non-linear transformation functions. Some (Andrews et al., 2002a; Wienhold et al., 2009) have suggested calling the relationship between suitability or utility and the value of the indicator variable as '*scoring function*' or '*scoring curves*'. To avoid confusion, we would prefer to retain the word function to operate as in the term soil function – an operation that soil performs, and propose here instead a new term, namely, *utility graph* – utility suggesting that the indicator gives an indication of the ability to do something (useful) and employing the word graph in the common definition "*a diagram showing the relation between variable quantities, typically of two variables, each measured along one of a pair of axes at right angles*"- and not the more rarefied mathematical definition.

Classical shapes for utility graphs are upper asymptotic sigmoid curve ("*more is better*"), lower asymptote ("*less is better*"), Gaussian optima ("*mid-point optima*")(Andrews et al., 2002a), although other forms may be of the binary type (0–1), stepped or categorical.

Many assessments compare different land uses or management practices (e.g. conservation agriculture vs conventional agriculture (Ghaley et al., 2018); conventional agriculture vs. biochar application (Llovet et al., 2021). The comparison between different land uses may require setting different utility graphs by land use, e.g. available phosphorus is related to productivity in forest stands and agricultural fields but the threshold level to fulfil the function nutrient storage differ largely equates with the recognition of different phenosoils. The performance of a soil function, service or potential risk of a soil threat will vary depending on the status of other functions/services/threats, and these relationships will be specific to the local management, climatic and pedological context (Schroder et al., 2016). This interdependence may be accounted for in the selection of the MDS, simplified empirical models adapted to site-specific conditions (e.g. C saturation equations for different dominant mineralogy (Six et al., 2002)) or parameterizing and shaping the utility graphs (Wienhold et al., 2009). Otherwise, the trade-offs and synergies can be quantified afterwards with correlation and co-occurrence analysis (Zwetsloot et al., 2020) or Bayesian networks (Vrebos et al., 2020).

5.3. Integration of scores into composite indices

The utility graphs provide sub-scores for individual soil functions/ threats to soil or their components, which can be integrated into a single index and later assigned into categories of overall soil functioning/ potential threat (Volchko et al., 2014). There are multiple methods for weighing and integrating the sub-scores, e.g. equal weights for each component, with weighted summation or with a fuzzy algebraic sum. The weights for integrating soil function scores or pressures of potential threats can be produced by expert knowledge (Gardi et al., 2013; Orgiazzi et al., 2016) or perception of the importance of individual function/pressures by the different stakeholders (e.g. (Manning et al., 2018); Mendes et al. (2021)), or calculated from the variation explained by relevant eigenvectors on PCA methods (Andrews et al., 2002a). An overview of methods for developing composite indices (weighing, aggregation) can be found in the OECD handbook (2008) or Greco et al. (2019).

The functional delivery of a soil is conditioned upon synergies and trade-offs between functions. For example, a change in soil management practice to improve primary production can negatively reflect on another soil function, such as carbon storage or provision of habitat for soil biodiversity. How the synergies and interactions between functions vary with land use, climate and soil type can be accounted for by modelling the multifunctionality of a soil. In the literature, several lines of work have accounted for interaction between functions, for example statistical modelling with Bayesian belief networks (BBN), multi-criteria decision modelling, and co-occurrence networks with correlation studies.

6. A comprehensive proposal

Having highlighted the various approaches to soil '*value*' assessment, we recognise approaches from previous attempts at soil valuation including concepts of soil functions multifunctionality, ecosystem services, soil quality and soil health. We recognise that the European concept of soil function is unique to soil science and has been developed ultimately to protect or secure soils. We also recognise the more general concept of services which were first manifested as ecosystem services; and finally, there has been a long history of studies and practices concerning soil degradation which may be efficiently assessed under the general heading threats to soil.

We now put forward the outlines of a comprehensive approach to soil security assessment. The aim of here is to present a systematic approach to the quantitative evaluation of soil security based on three (partially overlapping) roles:

1 *Soil functions* a collection of activities that soil can perform (arising originally from the European Commission framework).
2 *Soil services* a wider set of activities that soil can perform arising from the soil's ability to meet the six global existential challenges; this includes more than ecosystem services.
3 *Soil threats* (more correctly *threats to soil*) which also arise from the seminal European Commission framework. These are evaluated separately from soil functions to assess the resilience or buffering of the soil to external perturbations by virtue of use or location. However, we attempt to assess the resilience of soil, rather than the vulnerability or potential risks to soil.

By evaluating soil under these three roles, we hope to obtain a more complete picture of a particular soil or soilscape to support humanity, planetary functioning and its own existence. For each of the three roles, we outline the key categories under which each evaluation will be considered and review how they have been evaluated previously. In our outline assessment framework, we explicitly assess each sub-category of the role for each of the five dimensions of soil security. Potential methods that can be used for quantification approach, and combinations of multiple scores into composite index are also discussed.

6.1. Soil functions

6.1.1. Our definition

The ability of a soil to produce (and continue to produce) a particular outcome. A widely accepted definition is that soil functions are "*(bundles of) soil processes that underpin the delivery of ecosystem services*" (Bünemann et al., 2018; Glenk et al., 2012). The only hesitation we have with the terminology is the potential and actual confusion with the term soil functions with a mathematical meaning.

6.1.2. A comprehensive set of functions

There is no overall agreement on the list of functions between various sources, for example some literature aggregates nutrient, carbon and water cycling, as a single function while others disaggregate these into individual functions. Generally however, there is agreement around seven categories of soil functions (European Commission, 2006). The production of 'biomass' where soil provides the support for roots to explore for nutrients and water, enable the provision of food, fibre and aboveground biomass. The 'building' function identifies soil as providing raw material for both humans and animals to provide support for the building of roads, buildings and facilities. Collectively, these functions relate to *provisioning* services and these goods and services provided predominately have a direct economic value. Soil's ability to cycle 'nutrients', as well as store 'carbon', which is nature's contribution to the regulation of climate change. The ability for soil to store, regulate and filter 'water' is also enhanced by its function of storing and remediating contamination. These three functions share a relationship with *regulating* services and more commonly are accounted as having an indirect economic value. Soil also provides a function to protect and preserve 'biodiversity', which as a myriad of genes that can also be used to secure human health through the provision of the next generation in pharmaceuticals. Decisions around preserving this resource for future use, e.g. biodiversity, and climate mitigation, means they also can be valued as an option. The ability of soil to support natural environments for '*recreation*' and a store and preservation of our '*history*' services our *cultural* heritage service. Here, value is recognised for its '*existence*' or is '*bequested*' to other individuals or future generations, i.e. as passive values.

Several frameworks recognise that the soil serves as "*physical and cultural environment for humankind*" (Blum, 2005; European Commission, 2006), but we consider that different aspects of the historical, cultural and spiritual function of soils are comprehended by, and depend on the performance of other functions: directly (source of raw materials, archive of archæological artefacts) and indirectly through the sense of place and that results from the habitat, biomass and regulating functions, and hence is reflected in the connectivity dimension of each function. In addition, we want to put emphasis in the distinction between regulating the water cycle, the nutrient cycle and filtering and degrading contaminants. Thus, we propose to quantify the soil security dimensions of functions recognizing that the soil is:

1 A producer of food and biomass.
2 A store of carbon.
3 A habitat for, and of, biodiversity.
4 A store and regulator of nutrients.
5 A store, purifier and regulator of water.
6 A filter and remediator of contaminants.
7 A source of raw materials.
8 An archive of archæological artefacts.

The valuation of soil functions and soil-based ecosystem services (SES) builds on the concept of natural capital (Dominati et al., 2010; Robinson et al., 2009). In the framework proposed by Jónsson et al. (2017), soil *supporting* functions (soil formation, nutrient cycling, water cycling and biodiversity pool) are considered intermediary between the soil natural capital and the benefits that society obtains from the final ecosystem services and goods provided by soil. Therefore, support functions cannot be valued economically. However, there is some overlap between soil functions as defined in this proposal and SES, and hence we take the economic valuation of SES as a proxy of the capital dimension of soil security. A comprehensive review of the methods for economic valuation of SES and soil functions can be found in Jónsson and Davíðsdóttir (2016).

All these soil functions are inter-connected, and each unit of soil has the potential to provide all the functions simultaneously to differing degrees, depending on its land use, and the inherent soil's properties and processes, ascribing a soil as multi-functional. This multi-functionality and inter-connectedness provide many challenges to evaluate their value and their classification to the value classes described earlier. For each identified function, we indicate potential, but not exhaustive, indicators that characterise the five dimensions of soil security.

i. A producer of food and biomass. Soil is the primary medium for biomass production as well as the basis for agriculture providing feed for livestock and providing humans with 98.8% of daily calories (FAO, 2004; Kopittke et al., 2019). Soil facilitates plant growth by providing crops with essential nutrients, water, oxygen, root support as well as serve as a buffer protecting plants roots from drastic temperature fluctuations. The availability and security of food and biomass are fundamentally dependant on the capability of the soil which will determine the limiting factors of agricultural productivity.

Capacity Biomass production is the main soil function that signifies a direct relationship with crop yields, dry matter and biomass cover (Fischer et al., 2002; Mueller et al., 2010; Shepherd, 2003; Shepherd and Park, 2003). Intrinsic properties selected that indicate the capacity of a soil to support agriculture are the genosoil's available water content (AWC), rootable soil depth, texture (neither highly sandy or clay) or cation exchange capacity (CEC) (Vogel et al., 2019).

Condition From previous studies (Drobnik et al., 2018; Jäggli et al., 1998; Vogel et al., 2019), indicators considered are carbon content, soil structure, air capacity, plant available water, bulk density, hydraulic conductivity, pH, exchangeable cations (EC), earthworm abundance, species diversity and the abundance of macro and micro biodiversity.

Capital Soil directly contributes approximately AUD$ 63 billion per year to the Australian economy (Jackson et al., 2018) and approximately € 1675 billion in Europe (Scarlat et al., 2015) largely through biomass production. The valuation of food, feed and fibre is commonly assessed at the farm gate using yield value as a direct approximation. Gross margins for production and market prices, although indirect, are indicative of the value of soils to produce biomass.

Connectivity Consumers are becoming increasingly critical of the quality of their food, (Grunert, 2005) yet unaware of the ecological footprint of dietary choices (Marlow et al., 2009). Attitudes and willingness to pay for sustainably produced foods can give indication of the societal connection towards food production and its source.

Codification Overarching regulations or incentives placed on biomass production and overall soil conservation directly or indirectly are to be observed.

ii. A store of carbon. Soil organic carbon (SOC) stocks is estimated to range between 504 and 3000 PgC in the first metre of soil (Scharlemann et al., 2014). Soils act as a source or sink of carbon from the atmosphere depending on the balance between aboveground and belowground C inputs into the soil and C losses due to microbial decomposition of soil organic matter or erosion.

Capacity Indicators are the outputs of i) empirical models based on the concept of SOC saturation in the fine mineral fraction developed for different land uses and climatic zones (Feng et al., 2013; Hassink, 1997; Six et al., 2002; Wiesmeier et al., 2015), ii) data-driven models (Chen et al., 2019; Lugato et al., 2014) and iii) mechanistic and simulation models (Lugato et al., 2014). There is a divergence of opinion on whether the potential for long-term carbon storage should be estimated based on SOC pools of slow turnover time and mineral-associated SOC, or establishing references for the maximum SOC levels by soil type (e.g. SOC storage in genosoils in relatively natural conditions) or with modelling (Barré et al., 2017).

Condition As a dynamic property, current SOC content, has been widely used as indicator of overall soil condition. The current status of the C storage function is generally assessed with different indicators of SOC storage and SOC properties: SOC stocks (Vogel et al., 2019), SOC concentration (Llovet et al., 2021), SOC chemistry and fractions sensitive to management (e.g., particulate organic carbon) (Hoffland et al., 2020).

Capital The methods for valuating carbon storage or C sequestration include market price of carbon quotas, market cost of C sequestration technologies, or choice experiments. The value of carbon storage can range from $\$$ 20 to 268 kg ha^{-1} yr^{-1} (Jónsson and Davíðsdóttir, 2016).

Connectivity The society's perception of the importance of maintaining the soil carbon storage may be assessed by the awareness of its role for mitigating and adapting to climate change, and indirectly due to its positive influence on soil fertility and food quality production (Calvet-Mir et al., 2012). Other indicators are knowledge and training, cultural and technical skills for implementing C sequestration practices.

Codification There are several international directives and legal instruments destined to enhance the function of C sequestration, from the United Nations Framework Convention on Climate Change (UNFCCC) to the 2015 Paris Agreement (Hannam, 2021). An indicator of carbon storage codification could include the assessment of how effectively these policies are implemented, or the number of projects and or area contracted to carbon farming.

iii. A store and regulator of nutrients. Soils are a reservoir of nutrients providing plants with essential macro- and micro- nutrients needed for optimal growth. Soil stores nutrients left by the breakdown of organic matter and weathering of minerals. Nutrients are regulated by storage, transformation and translocation and has been considered a primary limiting factor of agricultural productivity in Africa and India (Pathak, 2010; Stewart et al., 2020).

Capacity Two aspects are within scope: (i) nutrient mobilisation capacity, which refers to the capacity of soil to provide available nutrients (mineral type) and (ii) nutrient buffering capacity (CEC and clay content) (Vogel et al., 2019).

Condition Vogel et al. (2019) suggests that the current nutrient stock is not to be considered as an indicator. Dynamic properties to assess the current state include soil organic matter, pH, and abundance of functional microorganisms that assist in mineralisation.

Capital The evaluation of the soil nutrient balance has been previously linked with farm economics and may be considered an indicator of capital (De Jager et al., 1998; Van den Bosch et al., 1998) as well as the cost to replace nutrients which can simply be measured by the cost of fertiliser applications.

Connectivity Soil fertility is highly valued amongst farmers as nutrient demand has intensified. The scale in which best management practices are adopted by farmers to reduce nutrient mining is a suggestive indicator for the connectivity dimension.

Codification As for codification, any regulations and policies enforced to prevent soil nutrient depletion such as limits of nutrient extraction and the replenishment of soil nutrients are to be assessed. Policies which incentivise fertiliser addition are common in many jurisdictions.

iv. A store, purifier and regulator of water. Soil has the ability to regulate water, whether as storage, run off or even drainage. Aside from water regulation, soil also purifies the water as it percolates through the profile through adsorption and precipitation (such as metals, pollutants), or through transformations of nutrients (i.e. denitrification process).

Capacity The capacity of a soil to regulate and purify water can be assessed with the soil water balance of the genosoil and its water holding capacity. The ability of soil to store water also depends on other factors, including porosity that can be linked to particle sizes (in particular clay content).

Condition The current ability of soil to regulate and purify water can be assessed through its AWC and current organic carbon content. Furthermore, as nitrate and phosphate are the main elements of concern within water bodies, denitrification capacity and phosphorus sorption capacity can be utilised as indicators.

Capital The global water market was valued at $\$$12.86 billion in 2020, and expected to grow up to $\$$ 22.97 billion (Fortune Business Insights, 2020) which seems to be underestimated. The water cycling function assessed with the replacement cost method has an economic value of $\$$ 62 – 126 kg ha^{-1} yr^{-1}, while clean water provision was valued at $\$$ 34 – 101 ML^{-1} (Jónsson and Davíðsdóttir, 2016). The willingness to pay for improvement of water quality as well as the avoided flood cost could be utilised as another measure of capital.

Connectivity There is a high connectivity with increasing consumer preference on safe drinking water (i.e. purified bottled water fortified with nutrients). Perceptions on the importance of soil functions, specifically water quantity regulation and water quality maintenance and enhancement were good predictors of compost use by Romanian farmers (Petrescu-Mag et al., 2020). However, under increasing climatic variability, a poor management could affect the soil's ability to function at its capacity, i.e. waterlogging can increase the rate of denitrification causing excess N loss.

Codification Various legislating bodies have been established to monitor and maintain water quality worldwide, i.e. Water Framework Directive (EU), Clean Water Act (USA), and National Water Quality Management System (Australia). With water scarcity occurring worldwide, management on water usage has also been implemented, i.e. green-blue water allocation policy.

v. A habitat for, and of, biodiversity. Soil is a habitat for micro- and macro-organisms, with more than 40% of living organisms in terrestrial ecosystems associated directly with soil (Decaëns et al., 2006). Relating soil biodiversity and function is a challenging research topic (Nannipieri et al., 2020).

Capacity There is a common belief that 'more is better' for soil biodiversity. Thus, the capability of soil biodiversity can be evaluated based on its genosoil's biodiversity. Soil pH buffering capacity can be used as another measure as the existence of a particular group of biodiversity.

Condition There are more than 200 methods that could be used to measure soil biodiversity (Griffiths et al., 2016). In an EU soil program, three indicators were used to represent taxonomical groups and functional levels (Bispo et al., 2009): 1) abundance, biomass and species diversity of earthworms, representing macrofauna; 2) abundance and species diversity of Collembola for mesofauna; and 3) microbial respiration for microbes. pH could also be utilised as another measure as it affects the group of microbes that exists on certain environmental conditions.

Capital While conservation biologists believe that every species has intrinsic value, the capital of biodiversity pool function is difficult to quantify. There has been a discussion on the ecological values and ecosystem services provided by soil fauna, however no monetary value was given (Decaëns et al., 2006). An estimate based on expert opinion has been attempted with a global value of $ 2.1 trillion per year based on the services that they provided (van der Putten et al., 2004). For agricultural land, a value of $ 430 $ha^{-1}yr^{-1}$ has been estimated (Jónsson and Davíðsdóttir, 2016).

Connectivity There is an increased awareness of soil biodiversity, in particular people see earthworms as ecosystem engineers. Citizen science projects such as identifying earthworm or other soil-living fauna communities, and Tea Bag Index (Keuskamp et al., 2013) can be a way of boosting connectivity. The measure of awareness would be the number of citizen science projects or participations per unit area of a particular soil.

Codification The UN Convention on Biological Diversity (CBD) in 1993 stressed the conservation of biological diversity, sustainable use of biological diversity, and fair sharing of benefits coming from biological diversity. Nevertheless, there is no policy yet related to soil biodiversity. Soil biodiversity is indirectly addressed on specific legislation on soil protection in some EU countries or regulations promoting environmentally-friendly farming practices (Turbé et al., 2010).

vi. A filter and remediator of contaminants. Soils denature pollutants and remediate heavy metals by filtering contaminated wastewater and immobilising organic contaminants into the soil matrix (Allen et al., 1994) and eventually breakdown of the contaminants (Yong, 2000).

Capacity The soil potential for contaminant sorption and filtration depends on the CEC, mineral type, reactivity via reduction/oxidation poise and hydrology measured by deep drainage (Mulligan and Yong, 2004). The mineralogy of the soil will influence the natural presence of some contaminants.

Condition The efficacy of the soil to naturally attenuate contaminants is dependant on numerous dynamic factors such as the organic matter content and microbiology. Soils with a higher presence of biochar are found to be more effective at eliminating both inorganic and organic pollutants (Hu et al., 2020). Within the complex microbial-biodiverse community of the soil, there exists host populations of organisms that assist in the decomposition of contaminants (Geerdink et al., 1996; Rajendran et al., 2003).

Capital Estimated global value of waste treated by soil is US$ 180 billion per year (Costanza et al., 1997; de Groot et al., 2002; McBratney et al., 2017b). For our approach, we consider monetising the benefits of soil towards the remediation of all forms of pollutants; inclusive of heavy metals, plastics, pesticide/fertiliser chemicals, organic and inorganic compounds. This is encompassed by the costs to treat contaminated soils, the value of soil free from contaminant as well as the market value of brownfields which can be evaluated to estimate capital.

Connectivity According to a study conducted by Brevik et al. (2020), key social determinants of human health in the soil includes soil pollution. This presents a useful indicator to develop a questionnaire for assessing the link between the medical community to soil toxins and human health (Soil Health Institute, 2018).

Codification An assessment of the environmental policies, regulations and incentives in place designed to prevent and regulate soil pollution (Glæsner et al., 2014; Heuser, 2022) can be used to quantify codification.

vii. A source of raw materials. The extraction of raw materials consists of the removal of components of soils that are in high concentration, usually accumulated in layers. This function is linked to many traditional customs such as production for building, pottery, or using peat as a fuel source. However, modern large-scale extraction of sand for concrete production (Gavriletea, 2017) and peat for agricultural production (Alexander et al., 2008) have an enormous environmental impact. This function, unlike others generally reduces soil security and is therefore questionable.

Capacity The main consideration is the natural quantity and quality of the material. Sand, clay and stone content will be the main indicators of quantity and mineralogy analysis is the main one for quality. For peat extraction, indicators will include the thickness and composition of the peat layer.

Condition Indicators such as soil strength or bulk density, and SOC content are generally used to measure the departure from the original soil and to monitor its recovery after sand extraction (Seguel et al., 2017). For peatlands, the thickness of the remaining peat layer is a key indicator (Alexander et al., 2008). A comparison of phenosoil created by soil material removal and a genosoil will help estimate the impact of removal activities.

Capital Most of the extracted materials have a well-defined market value. Smaller scale extractions to generate products such as pottery also have a well-defined market value. The cost of reducing other functions could also be quantified.

Connectivity For mass-scale extraction, the connectivity is removed and tends to zero. Small extractions are usually tightly related to cultural traditions where connectivity is high.

Codification In many countries, extractions are poorly regulated; or it is generally considered as mining activity. There might be some restrictions to extract from protected areas, but mining regulations usually prevail.

viii. An archive of archæological artefacts. Soils play a role in the preservation of a number of environmental remains, buried archaeological sites and are the support of cultural landscapes, but they also act as the medium for their degradation. This function was defined in Blum (2005) as a "*non-ecological*" function, which was labelled as "*geogenic and cultural heritage*". This function was more thoroughly described in Blum et al. (2022). The recent definition from the EU Commission kept the concept of heritage but is larger including the notion of cultural landscape: Concealing and protecting archæological remains; as a record of land use and settlement patterns (cultural landscapes), see a discussion in Pirnau et al. (2022).

Capacity Preferential conditions of the soils increase its capacity to store archæological remains, mostly pH drainage and redox potential for archæological materials. Depending on the remains, the soil conditions (either waterlogged, anaerobic or desiccating) and pH level (acidic or alkaline) will change the capacity of the soil to preserve the remains.

Condition Land use and climate change can affect the decay process and even change the nature of these processes (Davidson and Wilson, 2006) and this may affect in particular material sensitive to soil indicators such as skin, textile, etc. Soils of today in good conditions may results from past land management practices (Golding and Davidson, 2005). Condition can be manipulated to slow degradation and preserve artefacts.

Capital The loss of this function resulting from threats (urban development, mineral extraction, climate change, drainage, etc.) is difficult to monetise for societies. There is an important economic impact of having soils with high physical and cultural heritage (tourism, education, quality of life, job creation, construction).

Connectivity Connectivity is enhanced through a sense of belonging to the Earth in many societies, such as pre-Columbian, in opposition to western societies where myths come from the sky. Also in pre-Greek societies: "*mother Earth*" (as discussed in Blum et al. (2022)). Lahmar and Ribault (2001) provide many examples of connectivity of societies and religions to soils. Presence of human and cultural artefacts enhances connectivity and seeks to secure soil.

Codification The codification can be assessed via the presence of multiple levels of policy: global (e.g. the UNESCO World Heritage Convention), national, regional and site-specific management. Legislation for protection of cultural landscapes also exist, such as in France (bocages, etc.).

6.1.3. *Summary of soil functions*

By way of a summary, a tabulated list of potential indicators and utility graphs for soil functions for each of the soil security dimensions is presented in Table 1. The properties shown in the Table 1 are meant to be indicative and not a complete nor a definitive set of indicators.

6.2. *Soil services*

6.2.1. *Our definition*

Soil services are amenities that a soil can facilitate for the ongoing aid of humanity and planetary functioning. They are deliberately a longer list than simply ecosystem services but also recognise that soil offers assistance to a number of global existential challenges: ecosystem services respond to biodiversity and environmental challenges but there are desired soil services for energy, water and food security and for human health.

6.2.2. *A comprehensive set of services*

Soil services are not synonymous with soil functions – they probably

Table 1
Indicative list of indicators and utility graphs for a range of soil functions for each of the soil security dimensions. (↗) represents an increasing utility graph, (↘) a decreasing one, (∩) a mid-point optimum, (0,1) as binary, and as categoric al. The list is illustrative and not exhaustive. Note that some of the utility graphs (↗,↘) might not exactly follow a straight line relationship, but could potentially be sigmoid (,) or trapezoidal shape(,) based on certain threshold value.

Functions	Capacity	Condition	Capital	Connectivity	Codification
A producer of food and biomass	Genosoil's AWC (↗); rootable soil depth (↗); clay (↗); silt (↗); sand (↘); CEC (↗)	Carbon content (↗); AWC (↗); bulk density (∩); macro and micro biodiversity (↗); pH (∩); EC (↗)	Yield value (↗); gross margin ($ ha^{-1}) (↗); market prices (↗),	Awareness of sustainably sourced foods (↗); willingness to pay for sustainably source foods (↗)	Regulations and incentives on feed, fibre, and food production (0,1); regulations and incentives to conserve soil (0,1)
A store of carbon	Genosoil's carbon content (↗); Mineral-associated OC in the fine fraction (mg C g^{-1}) as function of fine particles (<20 μm) content (↗)	OC content (↗); OC:clay ratio (↗)	Carbon credit market price (↗); market cost of negative emission technologies (↘); cost of implementation C sequestration (↘)	Presence of carbon market (0,1); stakeholder's perception of the importance of maintaining the soil carbon storage from surveys (↗); level of training and knowledge on C sequestration practices (↗)	International-local directives on carbon storage regulation (0,1); policies and incentives for carbon farming (0,1)
A store and regulator of nutrients	Genosoil's clay content (↗); CEC (↗); mineral type ( )*	OC content (↗); AWC (↗); pH (∩); microbial abundance (↗)	Nutrient replacement cost (↘); Cost of fertiliser applications (↘)	Desire to implement BMP (i.e. nutrient management) (↗)	Regulations for extracting and replenishing soil nutrients (0,1); fertiliser bounties (∩)
A purifier and regulator of water	Genosoil's clay content (↗); AWC (↗)	AWC (↗); OC content (↗); Ksat (↘); denitrification capacity (↗); nutrient sorption capacity (↗)	Clean water value (↗); water market value (↗); willingness to pay for water quality (↗); avoidance of flood costs (↘)	Desire to implement BMP (i.e. improving drainage) (↗); awareness on safe drinking water (↗)	Regulations on water usage and water quality (0,1); soil water conservation (0,1); implementation of green water and blue water allocation policy (↗)
A habitat for, and of, biodiversity	Genosoil's biodiversity (↗); pH buffering capacity (↗)	Microbial abundance (↗); biodiversity (↗); pH (∩)	Ecosystem services value (↗); willingness to pay to protect mesofauna abundance (↗)	Awareness in participatory project involving non-expert, i.e. Tea Bag Index (↗)	Regulations around soil protection (0,1)
A filter and remediator of contaminants	CEC (↗); mineral type ( )*; redox poise (↗); deep drainage (↗)	Biochar (↗); microbial abundance (↗)	Cost to treat contaminated soil (↘); value of soil free from contamination (↗); market value of brownfields (↘)	Awareness of the impact soil pollution has on human health (↗); soil pollutant related medical research (↗)	Environmental policies regulating soil pollution (0,1)
A source of raw materials **	Sand, clay and stone content (↗); thickness of peat layer (↗); depth to bed rock (↗)	Soil strength or bulk density (↗); OC content (↗)	Market price of material (↗)	Proximity to site (↘); extraction scale (↘)	Policies regulating extraction and restoration (0,1)
An archive of archæological artefacts	pH buffering (∩), redox poise (↗); specific heat capacity (↗)	pH (∩), soil temperature (↘), redox potential (↘)	Cultural heritage value (↗)	Sense of belonging in earth (↗)	Legislation for cultural landscape (0,1)

* Categorical level to be determined;.
** Positive values contribute negatively to soil security; Abbreviations. AWC: Available Water Capacity; BMP: Best Management Practices; CEC: Cation Exchange Capacity; EC: Exchangeable Cations; OC: Organic Carbon.

have a higher level of generalisation. Perhaps more elegantly, a set of soil functions could be constructed to be used in various combinations to measure any particular soil service – but that notion has not been developed here. We do recognise that there is some overlap with evaluation of soil security dimensions via soil functions. Here, we consider the following comprehensive set of services:

1 Environmental/ecosystem maintaining.
2 Climate change mitigation and adaptation.
3 Water securing.
4 Biodiversity protecting.
5 Human health mitigating.
6 Food and nutrition securing.
7 Energy securing.

i. Environmental / ecosystem maintaining. Soils provide a great number of services that directly maintain or enhance the ecosystem. These services are broad and a few examples of these include: soil formation, biological control of diseases through the absorption of pathogens, soil stabilisation through erosion control and sediment retention (Comerford et al., 2013), amongst others.

Capacity Soil formation governs the landscape, biological populations present and determines soil physical, chemical, and biological properties. These factors can be assessed by the five soil forming factors; climate, organisms, relief, parent material and time (Jenny, 1994) and are summarised by any comprehensive soil taxonomy, e.g. Soil Taxonomy, World Reference Base, at an appropriate categorical level, e.g. the family.

Condition Soils serve in the retention and regulation of a variety of fungal, bacterial, and viral pathogens and pests of plants and animals through a series of biotic and abiotic attributes (Mazzola, 2002). Dynamic soil properties such as soil temperature, pH, organic carbon content and exposure to sunlight has also been proven to influence both pest and pathogen survival (Anderson and Sutherland, 1989; Glenn and Dilworth, 1991; Menzies, 1963).

Capital Soil is evaluated based on the market price and the biological control of pests and diseases are evaluated by the both the avoided cost to restore the ecosystem from an outbreak and provisional expense which is the anticipated expense of the biological control (Jónsson et al., 2017).

Connectivity There is an increasing awareness of the public to protect ecosystems although there is a disconnection to the direct conservation of soil often not seen as a priority (Eusse-Villa et al., 2022). A survey in sustainably marketed goods to determine whether soil conservation is recognised as integral to environmental sustainability which is extensively used in marketing towards the growing consumer demand for sustainability.

Codification Overarching policies established to protect entire ecosystems may be assessed. This includes the presence/absence of regulations regarding deforestation, mining, and soil pollution/contamination around the world.

ii. Climate change mitigation and adaptation. Soil has an essential role in climate change mitigation and adaptation through its role in the global C cycle. Human activities through land use change and intensive agriculture have accelerated soil C loss. It is estimated that soils contributed around 60% of total N_2O emissions (Tian et al., 2019). This in turn caused about 3.7% of the global increase in radiative forcing due to anthropogenic greenhouse gas emissions (Kopittke et al., 2021).

Capacity The capacity of the soil to climate change mitigation and adaptation relies on soil carbon; and thus, indicators for capacity of soils as a store of carbon are applicable here.

Condition Similarly, the amount of carbon in the soil would reflect its condition. In addition, the ground cover would be an indicator of soil condition related to albedo and radiative forcing.

Capital Similar to soil functions and carbon store and threats of decarbonisation, now there is a growing recognition of soil carbon as a greenhouse gas offset and market for soil carbon is growing.

Connectivity Climate change has boosted soil carbon as a nature-based negative emission technology. There has been a boost in the number of popular articles on soil carbon, which reflect that connectivity is high. This is discussed on the function of soil as a carbon store and decarbonation threat. Other measures might include the awareness of green energy (smart appliances and solar powered), and shift in preference towards improved vehicle efficiency,

Codification Under international climate agreements, targets on reducing greenhouse gases emissions have been discussed in Kyoto Protocol, as well as under the Paris agreement. The local implementation of regulations to achieve these targets could serve as an indicator.

iii. Water securing. The pore system of soils has the capacity to accept and store water which can then become available to plants when rainfall is not available. Also, within soils exists different mechanisms that allow them to immobilise solutes or suspended materials, acting as a filter (Keesstra et al., 2012).

Capacity The volume and architecture of the pore system (size and distribution of pores) are what mainly control this service. Direct indicators would be available water content and hydraulic conductivity. Simpler to measure soil indicators would be bulk density, organic carbon content, structural form (pedality) and particle-size distribution.

Condition Compaction and loss of organic carbon directly affect water mobility and the capacity of the soils to store it. Changes in bulk density, soil organic, structure and the resulting changes in available water content and hydraulic conductivity are the main indicators. These can be assessed via a phenosoil – genosoil comparison.

Capital For a particular location, improved water storage could reduce the need of irrigation and dams and their associated infrastructural costs. The increased value of stored water could be assessed through irrigation water prices. At larger scale, filtering plays an important role in groundwater quality, and could be quantified via cost of flood mitigation.

Connectivity In general, it is an “invisible” service and its connectivity is probably generally small. Farmers are aware of the importance of soil water storage, which directly affects their production, which would result in high connectivity. Measurement may be possible via questionnaires around water quality and availability and soil capacity and condition or via measuring the uptake of water conservation practices.

Codification This can be measured by the presence of soil-based water conservation practices. Some countries give benefits to farmers to improve the quality of their soils, including the water storage capacity (by increasing SOC and improving physical properties).

iv. Biodiversity protecting. “*Soils are a reservoir of biodiversity. They provide habitat for thousands of species regulating for instance pest control or the disposal of wastes*” (Dominati et al., 2010), but the soil service of protecting biodiversity comprises soil biodiversity (addressed in the soil functions role) and aboveground biodiversity. Soils sustain aboveground biodiversity directly, through specific interactions between soil and aboveground organisms (e.g., food webs, ground-nesting pollinators), and indirectly by enhancing ecosystem functioning (Lavelle, 2012; Parker, 2010).

Capacity Inherent properties like soil texture influence the soil’s ability to constitute suitable habitats, influence the aeration and soil hydric regime that affect the soil microbial communities, and soil meso- and macro-fauna. The relationships between plant communities, soil inherent properties and soil services (van der Plas et al., 2016) are characterised by strong feedback loops while the vegetation community co-evolves with soil during ecosystem succession (Havlicek and Mitchell, 2014).

Condition A soil's potential to protect the soil biodiversity for site-specific conditions is strongly driven by dynamic properties interconnected with soil biota like soil structure and the spatial organisation of the mineral particles (aggregates, porosity), biodiversity and soil pH.

Capital While the value of soils as biodiversity pool has been estimated (van der Putten et al., 2004), it may not be straightforward to assess the contribution of soil to the value of overall ecosystem biodiversity. A possible proxy could be valued with the willingness to pay for soil management projects directed for biodiversity conservation (Pearce, 2007).

Connectivity The connectivity of the society with the service of biodiversity conservation may be higher for vertebrates, animals with whom humans feel are more similarities, than with soil fauna and biodiversity with whom an emotional link is missing. The level of knowledge and awareness of the relevance of soils for maintaining overall ecosystem biodiversity could be assessed with surveys.

Codification Policies directed to protect aboveground biodiversity do not suffice for preserving soil biodiversity whereas most soil policies do not focus on biodiversity conservation (Zeiss et al., 2022). Policies that protect soils in their integrity may be most effective to guarantee the contribution of soils to biodiversity protection according to their capability.

v. Human health mitigating. Soils are a medium where biochemical transformation can affect human health directly through the provision of clean air and water, or indirectly through emission of gases (CO_2, CH_4). Soils also mitigate anthropogenic and biological material transfer to humans. In Nieder et al. (2018, pg vii), the authors give a list of the nefarious effects of soils that directly affect humans, most of them depict harmful impacts, in particular, due to direct or indirect contact with soil (geophagia, contact with potentially toxic natural and anthropogenic dusts, micro- or macro-nutrient deficiency, toxic elements, radon). These negative effects that soils cause to humans have been conveyed by terms such as "*disservice*" (Power, 2010) or disamenity (Simpson, 2011).

Capacity Intrinsic biogeochemical factors (natural conditions and environmental geochemistry) and soil hydric regimes generally affect the ability of the soil to mitigate human health. Specific indicators include concentration of trace elements (e.g., to assess microelement supply and toxic elements to micro-organisms), soil texture and agricultural production (e.g., for airborne dust Se and Pb), or thorium, uranium, potassium and caesium (e.g., for radionuclide).

Condition In addition to the ability of the soil, a number of anthropogenic additions affect this service water infiltration, regulation of pests and pathogens, erosion control, nutrient and added micro- and macro-elements, industrial organic substances. A combination of natural factors and man-made pollution, for example human faeces which contaminate the soil and enable transmission of eggs from parasitic worms (e.g. helminthiasis), or man-made release of radionuclides (e.g. nuclear waste, tests, accidents). Crop yield may be an indicator for micro and macro-nutrient deficiency.

Capital There is a possibility to monetise discoveries from soil-borne pathogens and diseases. The production capital of soils depleted in trace elements in diminished- human communities cannot live on crops which render hidden hunger due to micronutrient depletion. The capital of polluted soil by radionuclides is low and can be assessed by cost of removal or remediation, with recent examples on the soils surrounding Fukushima in Japan.

Connectivity Geo-/pedo-phagia eating soil/clay arising from medicinal/physiological and nutritional factors. Higher fulfillment provides higher connectivity, but this is mostly in the case of local consumptions of food from soils. There has been improved connectivity as human health was introduced to the sustainable development agenda by United Nations, addressing both malnutrition, and hidden hunger issues (Oliver and Gregory, 2015). Overall, measurement of the awareness by local populations of links between medical conditions and soil condition or capacity is required.

Codification The presence of health regulations which specifically recognise soil agency in human health. All regulations related to carbon storage in soils and unintentional man-made formed organic substance, regulations against or soil and groundwater pollution.

vi. Food and nutrition securing. Currently, it is estimated that securing the food provided by soil requires approximately 1600 million ha of production land for crops and a further 3200 million hectares of soil dedicated to permanent grasslands and pasture (FAO, 2021). This equates to nearly 40% of the land mass prioritised for food security leaving the rest to provide for the other soil functions described earlier (Kopittke et al., 2022). This is further complicated by the need for the soil to continue to provide the required nutritional balance providing the emerging focus beyond calorie intake to ensuring nutritional security (Hwalla et al., 2016).

*Capacity [*Land suitability assessment has a long history that would be analogous to assessing the soil's capacity to produce food or land that should be reserved as conservation or to lessen the impact of degradation. The versatility index (Kidd et al., 2015) assesses and maps soil properties that evaluate the diversity of food production. Some of the indicative property that can be potentially used include rootable soil depth, and CEC.

Condition Having access to land that is capable of producing food and is in good condition is affected by sufficient access to management strategies and resources to secure food production and are adaptable to the impacts of climate change and other external forces (Chivasa, 2019; Pozza and Field, 2020). Some of the potential indicators include pH, available water capacity EC and micronutrient content. The increasing demand on food is impacting soil's condition through land intensification and further degrade the soil's condition and impacts its ability to also provide other soil functions (Lal, 2020; Landis, 2017; Squire et al., 2015).

Capital Deriving value aligned with food security directly can be measured by the value of the commodity produced (Kidd et al., 2015) but undervalues the other functions that the soil also provides, or misses the value derived from non-monetary sources such as 'care' (Pozza and Field, 2020). More complex approaches based on soil data derived from digital soil mapping protocols has the potential to translate selected soil indicators into measures of capital, as well as value linked to peoples connectivity (Richer-de-Forges et al., 2019; Robertson et al., 2012). Land tenure has strong impact how land is valued and its subsequent sustainable management (Hartvigsen, 2014; Obeng-Odoom, 2012). If tenure is short or insecure, farmers will be less likely to invest time and money into soil conservation, new technology, and sustainable cropping systems (Besley, 1995; Fraser, 2004; Lovo, 2016).

Connectivity The connectivity the food producer has with their land is serviced by having developed education capacity building strategies (Pozza and Field, 2020). The well-established consumer connection to land through a value beyond monetary is exemplified by the terroir concept and has the potential to expand to other commodities where soil condition or 'health' have the potential to be recognised (Chan, 2012; Lambot et al., 2017; Nesto, 2010; Turbes et al., 2016) and used as indicators. The implementation of certification schemes creates a link between connectivity and codification by providing a form of governance and may assist with sustainable management.

Codification The delivery of certification programs linked to food products and trends in environmental certifications is driven by consumer demands to ensure that their products are produced sustainability. The inclusion of soil indicators supporting this and recognising the provenance of the food products may be indirectly linked to this approach. The implementation of land classification systems such as; Land Environments of New Zealand classification (Manaaki Whenua - Landcare Research, 2019), Biophysical Strategic Agricultural Land (NSW Government, 2019), and the Provisional Agricultural Land

Classification in England and Wales (Natural England, 2019), and the need for on-farm best practice soil management plans (Kidd et al., 2015) are increasingly requiring soil indicators which can similarly we used to assess the codification.

vii. Energy securing. Soils have both direct and indirect impacts on available energy. The depletion of conventional fuels, such as petroleum products and environmental concerns are the driving forces into exploring renewable source of energy. Large quantities of biomass are being produced globally, which can be potentially transformed into biofuels.

Capacity indicators for energy security will include all those which would define biomass production (if biomass is seen as a source of renewable energy.) – primarily available water, pH and nutrients. Secondarily, we could consider those soil indicators that are likely to contribute to carbon neutrality.

Condition Indicators in phenosoils which might differentiate would include reduced available water, structure, pH and nutrient changes and possible compaction (bulk density). Contamination might not be an issue – as the purpose of production is not for human consumption. Secondarily, storage of heat energy (e.g., soil temperature at 50 cm) and differential emission of greenhouse gases (especially methane, nitrous oxide) would be indicators.

Capital The capital value of soil for energy production is related to biomass production. The negative capital of greenhouse gas production and reduced value of ecosystem services under biomass energy production could also be estimated.

Connectivity This could be measured inter alia by consumers desire to use energy. The public's attitude to energy versus food production preference for genosoils and phenosoils could also be measured.

Codification This could be quantified by measuring regulations around (a) energy production versus food production, (b) limits on greenhouse gas production.

6.2.3. *Summary of soil services*

By way of a summary, a tabulated list of potential indicators and utility graphs for soil services for each of the soil security dimensions is presented in Table 2. This list is illustrative and not exhaustive or definitive.

6.3. *Threats to soil*

We prefer the terminology '*threats to soil*' over the shorter '*soil threats*' because the latter suggests that the soil is a threat to humanity or the planet. There are instances of course where this is the case, e.g. dust from soil, soil naturally high in lead – so there are threatening or hazardous soils. Philosophically we can ask if these should be secured if they are seen to be part of the '*natural'* environment? Threats to soil have been long recognised but the list has grown over the decades and now are synonymous with a range of soil degradation processes, some of which are 'speeded up' natural processes.

6.3.1. *Our definition*

Threats to soil is a set of soil-degrading processes which reduce soil functionality and service ability and the existence of soil itself.

6.3.2. *A comprehensive set related to soil process*

When we consider threats to soil, the capability relates to that which makes the soil vulnerable to the threats. This can be assessed based on how resilient / buffered the soil is against the threat. Such a consideration is related to concepts of soil fragility, soil vulnerability and soil resilience. The inherent fragility (Clunes et al., 2022) of a soil that has little resilience causes that any anthropic pressure reduces one or several functions severely to a point from which it cannot recover and becomes unstable. A soil with higher resilience will overcome anthropic pressures, but its ability to perform soil functions may decrease progressively while its fragility will increase, perhaps reaching a point of no return

Table 2
Indicative list of indicators and utility graphs for a range of soil services for each of the soil security dimensions. (↗) represents an increasing utility graph, (↘) a decreasing one, (∩) a mid-point optimum, (0,1) as binary, and as categorical. The list is illustrative and not exhaustive. Note that some of the utility graphs (↗,↘) might not exactly follow a straight line relationship, but could potentially be sigmoid (,) or trapezoidal shape(,) based on certain threshold value.

Services	Capacity	Condition	Capital	Connectivity	Codification
Environmental maintaining	Soil class ( )*	Soil temperature (∩); pH (∩); OC content (∩);	Market price of soil (↗); provision expense of an outbreak (↘)	Awareness and moral obligation to protect soil (↗); consideration of soil conservation (↗)	Soil integrity protection policies (0,1)
Climate change mitigation	Genosoil's carbon content (↗); specific heat capacity (↗)	Current carbon content (↗); ground cover (↗)	Soil carbon credit offset (↗)	Awareness of soil carbon management practices (↗); awareness of green energy (↗)	Soil carbon policies (0,1)
Water securing	Genosoil's carbon content (↗); structure grade ( )*	AWC (↗); OC content (↗); hydraulic conductivity (↗); bulk density (↘)	Costs of irrigation water (↘); water filtering value (↗); costs of flood mitigation (↗)	Awareness of productive value of water (↗); implementation of water conservation practices (↗)	Water efficiency policies (0,1)
Biodiversity protecting	Soil class ( )*; Endemic soils	Soil structure, porosity, pH (∩); (functional) biodiversity (↗)	Willingness to pay for biodiversity conservation (↗)	The awareness of the ecosystem biodiversity maintenance (↗)	Existence of policies that protect soils integrally (↗); biodiversity acts incorporating soil biodiversity (0,1)
Human health mitigating	Genosoil's concentration of trace elements, radionuclides, and organic biocides (↘)	Concentration of radionuclides, heavy metals, exogenous organic molecules (↘)	Value of nutritious produce (↗); health expenses related to deficiencies and toxicities (↘)	Awareness of source of food related to food chain, i.e. geophagia (↗)	Regulations related to carbon storage in soils, man-made organic substances, contamination concentration limits (0,1)
Food and nutrition securing	Rootable soil depth (↗); CEC (↗)	pH (∩); EC (↘); ESP (↘); bulk density (↘); micronutrient (↗)	Direct use valuation – gross margin (↗); costs of depletion (↘)	Implementation of BMP on farms (↗)	Regulation of agricultural land, i.e. prime agricultural land (0,1)
Energy securing	AWC (↗); pH (∩); nutrients (↗)	AWC (↘); structure, pH and nutrient changes, bulk density (↘)	biomass production value (↗)	Desire to use green energy (↗); attitude to energy vs food production (↗)	Regulations on energy production versus food production (0,1); regulation to limit greenhouse gas production (0,1); competing land use policy (0,1)

[*] Categorical level to be determined; Abbreviations. AWC: Available Water Capacity; BMP: Best Management Practices; CEC: Cation Exchange Capacity; EC: Exchangeable Cations; ESP: Exchangeable Sodium Percentage; OC: Organic Carbon.

after anthropic interventions (Clunes et al., 2022).

Here, we consider the following threats to soil:

1 (Accelerated) erosion.
2 Acidification.
3 Salinisation.
4 Decarbonisation.
5 Contamination.
6 Soil structural decline.
7 Habitat loss/degradation.
8 Soil sealing.

i. (Accelerated) erosion. Natural erosion has positive aspects in landscapes. The movement of soil and sediment transport via wind and water is often responsible for the formation of fertile alluvial, colluvial and loessic soils that support agriculture by increasing the rooting depth in deposition sites. Anthropogenic erosion or human-induced erosion accelerates and intensifies this process. The magnitude of accelerated erosion affects the soil's ability to perform its natural functions affecting the productivity and stability of all ecosystems. Over time, erosion has been associated with human interaction and is now recognised as a major global threat (Lal, 2001; Montgomery, 2007; Pimentel and Burgess, 2013).

Capacity Inherent soil properties that influence erosion susceptibility include; dispersion ratio (Middleton, 1930) and aggregate stability (Barthès and Roose, 2002), and particularly the shear strength of the soil surface which will vary with moisture content and rooting density. A surrogate such as surface cover is often used.

Condition Erosion is known to be accentuated in areas with unsuitable agricultural practices, harsh climates, steep topography, and poor structural conditions. For water erosion, the revised universal soil loss equation (RUSLE) uses the following soil characteristics to indicate intensity of erosion; degree of slope, slope length and ground cover (Van der Knijff et al., 2000). As for wind erosion, surface bulk density and soil surface moisture are important indicators (Visser et al., 2004).

Capital Human induced erosion has affected 15% of the earth's total land area (Bridges and Oldeman, 1999). In 2016, the FAO global soil partnership estimated a loss of 75 tons of soil per year from arable lands at a value of USD$ 400 billion (Food and Agriculture Organization [FAO], 2016). The method of avoided cost can also therefore be attributed as a capital value.

Connectivity This threat is exacerbated by the current trajectory of intensive land use or ameliorated through soil conservation practices. Erosion has also become a growing research topic for both physical and social scientists where the number of erosion research papers outside of soil science can indicate connection across disciplines. Uptake of soil conservation practices is an indicator of connectivity here.

Codification This dimension may be quantified by assessing number of regulations enforced and incentives placed across all landforms and environmental settings that directly and indirectly target erosion such as the Good Agricultural and Environmental Conditions (GAEC) for land framework in Europe.

ii. Acidification. While acid soils can be naturally formed the process of acidification results from anthropogenic processes, including excess application of fertilisers, crop removal, acid rain and exposure of acid sulphate soils through drainage. Agricultural land management is a significant factor affecting soil acidification (Koch et al., 2015) and with the intensification of agricultural production and increased use of fertilisers there is concern this will continue (Kopittke et al., 2019). While topsoil acidity can be corrected, it is the subsoil acidification that is extremely concerning, where remediation strategies are limited. A comprehensive review of soil acidification, its impacts, management and relationship to greenhouse gas fluxes is provided in Kunhikrishnan et al. (2016).

Capacity The pH buffering capacity of the soil will strongly affect the soil's ability to respond to the external pressures leading to its natural pH change and would be an indicator of the soil's capacity contributing to its capability. This buffering capacity would be largely affected by the clay content, mineral suite, and organic matter.

Condition The current pH of the soil reflects its condition where a pH below 5.5, where up to 40% of Australia's landmass has a pH < 4.0 being classified as highly acidic (Kunhikrishnan et al., 2016) would be considered as acid, affecting plant performance and the availability of toxic elements, such as aluminium. Assessing the soils pH over a period of time would confirm if acidification were occurring. A comparison of genosoils and phenosoils would be critical in assessing this threat.

Capital In addition to measuring and mapping the current soil's pH, modelling the potential change in pH using the soil's buffering capacity and estimating the impact of soil acidifying practices (e.g. fertiliser management) would enable changes in the soil pH to be predicted over time. These pH values can then be translated into costs associated with loss of productivity and/or amelioration (e.g. liming) to mitigate the impact.

Connectivity The general acidification pressures on the soil are in response to the soil's management (e.g. addition of nitrogen fertilisers) and its ability to recovery through remediation strategies such as liming. Assessment of the soil's buffering capacity and changes in its condition through lime requirement models provide the connectivity needed to predict the potential increase in soil pH with continued management practices (Singh et al., 2003). Measurement of liming or fertiliser practice yield an estimate of human connectivity to this threat.

Codification Policies and regulations requiring the mapping and monitoring of soil pH and change in the pH over time would be an indicator addressing areas where soil acidification is occurring and encourage the implementation of management strategies through compliance.

iii. Salinisation. Soil salinisation is an important degradation process consisting of the accumulation of soluble salts in the rooting zone of the soil. Natural salinisation is mainly associated with arid and semi-arid regions where evapotranspiration exceeds precipitation, which is not enough to dissolve and leach salts. The source of the salts is natural (parent material, groundwater and sea) but where the source is human-induced excessive fertilisation or poorly designed irrigation with low quality water (Vengosh, 2003) then we have threat of (accelerated) salinisation.

Capacity The main indicator is the electrical conductivity of the saturated paste extract (EC) and the exchangeable sodium percentage (ESP) and the presence of surface efflorescence and halophytic plants.

Condition Changes in EC and ESP compared to natural conditions (genosoil/phenosoil comparison) can indicate if management is promoting the salinisation. Increasing development of columnar structure may be an indicator of the ancillary process of sodification.

Capital Salinisation has a negative impact in crop production which has direct economical impact that can be quantified. Some estimates include AUD$ 200 - 300 million per year in Australia and $ 270–960 million in Pakistan (Sakadevan and Nguyen, 2010).

Connectivity In agricultural production, the effect of salinisation is easy to observe (loss of production), hence farmers probably have a high connectivity, therefore a survey of landholders on the effect of salinisation and mitigation practices would gauge connectivity.

Codification Potential indicators include regulations regarding fertilisation and irrigation. Also, the existence of incentives to improve soil already affected by salinity/sodicity is another possible indicator.

iv. Decarbonisation. Intensive agriculture has been the main cause of soil decarbonisation. Estimates range from 30 to 50% of soil's initial organic carbon content had been lost after 10 - 20 years of cultivation.

This rapid decline is due to the removal of native vegetation that continually supply carbon into the soil and the rapid decomposition of soils exposed to cultivation. Globally, it has been estimated that around 60 - 85 Pg SOC had been lost in agricultural soils due to intensive cultivation (Padarian et al., 2022). Less discussed is the threat to inorganic carbon (SIC) which accumulated in the soil as pedogenic carbonate or from parent materials. Agricultural practices, especially ammonium-based fertilisation results in soil acidification that causes the SIC loss (Zamanian et al., 2018).

Capacity The capability of the soil to store more carbon can be determined based on process-based modelling or an empirical approach. The capacity is controlled by extrinsic climate factors but probably the most important intrinsic soil factor is the amount of adsorption or charge which can be measured by the clay (and silt) content and mineralogy. Clay (and silt) divided by CEC may be a good proxy indicator of potential capacity.

Condition SOC and SIC content would reflect much of the soil conditions. SOC can be audited with great confidence with proper sampling methodology (de Gruijter et al., 2016). In addition, SOC fractions such as mineral associated or particulate organic carbon would reflect the amount of C protected and available for plant microbes. An empirical approach is the ratio of SOC to clay that indicates the level of OC saturation, with a value of 1/10 considered as a good ratio. Values lower than a threshold that is climate and soil specific would be considered degraded (Prout et al., 2020). Ratios for subsoils are less clear. Another benchmark is a comparison with the level of SOC or SIC of a local genosoil.

Capital The pursuit of net zero emission has boosted soil carbon as a nature-based offset. There is a continuing demand for CO_2 offsets, with a value in Australia set around $ 15 per tonne CO_2 since 2019 to a market price over $ 50 per ton CO_2 in 2022 (Wood and Reeve, 2022).

Connectivity Soil carbon has gained prominence in the world of organic and regenerative agriculture. The adoption of regenerative practices or carbon farming could be a measure of connectivity. In addition, the labelling of organic or sustainable produce may indicate the demand or awareness of produce grown on healthy soils.

Codification There has been various policies in soil carbon as part of climate change mitigation. At the global level, the UNFCCC Kyoto Protocol recognised soil carbon as a sink. The most relevant at the country level include the inclusion of soil carbon in the Nationally Determined Contribution (NDC) emission reduction (Wiese et al., 2021). Government-supported soil carbon offset schemes are another policy mechanism that secures and enhances soil carbon.

v. Contamination. Contaminated soils are soils in which the chemicals (inorganic and organic compounds) are at a concentration that cause potential risks to humans and the environment. FAO estimated that soil pollution affects the production of safe and sufficient food, compromising global food security (Díaz et al., 2019). This threat is strongly related to the disservice human health mitigating as it is a threat to soil, but also to the environment and to the human (Morgado et al., 2018). This threat occurs in nearly all cases as a result of man-made point or diffuse sources (Gregory et al., 2015).

Capacity The diversity of organisms is one of the main indicators of soil vulnerability to contamination, as greater diversity usually means more toxicological processes acting within the soil. Other indicators would involve soil organic and inorganic adsorption characteristics.

Condition Pollutants induce changes in all kinds of biota, related to C, N, P, and S cycles and their sensitivity to contamination. N-deposition affects pH and hence biodiversity. Earthworms and springtails are sensitive to metals and could be used as indicators. Metabolic quotient and microbial respiration are indicators of Cu and Zn pollution. The fate of pollutants is also determined by a number of pore-scale processes abiotic degradation, redox processes, precipitation and ion exchange, amongst others, but a number of indicators related to soil biological and chemical properties can be used.

Capital The capital value of contaminated soils depends on the financial consequences of ignoring the pollution and its effect or the financial consequences or management consequences for de-pollution. It depends on the destination of the land and the connectivity. Economic loss due to soil pollution and contamination in terms of increased use of agrochemicals, unsafe food and polluted water (indirect loss of biodiversity).

Connectivity Soil waste dumps (industrial and household) polluting soils, coal gas, petrol station, pesticides decrease connectivity. Connectivity can be assessed by the ability of human population to assess contamination (López-Aguilar et al., 2022) and their willingness to mitigate it.

Codification Many governance and legal frameworks to tackle soil pollution have been developed including a soil protection framework in the EU, an International Code of Conduct on Pesticide Management (Pesticide Code), adopted by FAO Member Nations in 2013, Global Action Plan on Antimicrobial Resistance, International Code of Conduct for the Sustainable Use and Management of Fertilisers (Fertiliser Code).

vi. Soil structural decline. Soil structural decline refers to the destruction of aggregates and loss of soil structure resulting from several processes like loss of organic matter, irrigation or leaching of saline-sodic soils (Bethune and Batey, 2002), compaction caused by traffic of agricultural machinery (Batey, 2009). This threat has cascading effects on several soil functions (water regulation, habitat for biodiversity, carbon storage) (Rabot et al., 2018) and is related to other threats (e.g., accelerated erosion, decarbonisation).

Capacity The soil's inherent fragility and resilience to structural decline will vary with the stage of soil development and soil type. Soil physical properties in interaction with environmental factors (climate and relief) will determine the soil's susceptibility to irreversible loss of functionality linked to compaction caused by machinery traffic (Batey, 2009; Ward et al., 2021). Aggregate stability of genosoils would serve as a good indicator of inherent soil structural stability.

Condition This dimension is probably the most relevant for estimating the resilience to soil structural decline, as soil structure is a dynamic attribute itself that results from the interaction between biotic and abiotic soil components (organic matter content, porosity, aggregate stability, soil meso- and macrofauna). Multiple field visual estimates, laboratory analyses and semi-automated imaging techniques can be applied to estimate the current condition of soil structure in relation with several soil functions (Rabot et al., 2018). A comparison between genosoils and phenosoils would indicate the quantum of change.

Capital The method of avoided costs or replacement costs could be applied to quantify the (loss of) capital associated to soil structural decline. The effects of soil compaction and structural decline on farm yield loss was estimated to be $2 billion annually for the USA and $ 0.8 billion for Canada for the year 1990 (Lal, 1991).

Connectivity This dimension can be assessed by surveying the knowledge of farmers on the effects of soil compaction on yield decline. Another indicator could be the number of workshop days spent by soil users on soil structure mitigation and extension programs.

Codification Policies and incentives for reducing the traffic of agricultural machinery (e.g., no tillage) and the loss of carbon are relevant indicators.

vii. Soil sealing. Soil sealing, unlike some of the other threats to soil is not an accelerated natural process. It is the loss of soil resources due to covering by impermeable material. Soil sealing was identified as one of the main soil degradation processes in the Soil Thematic Strategy (European Commission, 2006) as future generations would not be able to see the healthy soil comes back within their lifetime (European Commission, 2012). Soil sealing driven by urban sprawl is characteristic of numerous cities nowadays as a phase of a country's development towards modernisation.

Capacity The capacity of soil to be resilient to soil sealing can be measured using the identification of soil property that prevents the occurrence of soil sealing in the first place, i.e. shrink-swell capacity, linear shrinkage. Soil sealing directly influences the soil's functions (i.e. food and biomass production, biodiversity and potential carbon sequestration (Seto et al., 2012; Tobias et al., 2018)) and its regulating services (i.e. prohibiting water infiltration and causing stronger surface run-off (Du et al., 2015; Scalenghe and Marsan, 2009)). Parameters that could be used include legacy land use data. Other proxy indicators that measure water infiltration rate could also potentially be used, i.e. clay content and aggregate stability.

Condition The current land use type and land take rate (Ronchi et al., 2019) can be used to identify urban expansion. Another possible proxy index is common urbanisation intensity index (CUII), which measure the urbanisation intensity for a spatial unit during a certain time span, which could be an effective method to reflect the dynamics of soil sealing due to urban sprawl (Li et al., 2018).

Capital The occurrence of soil sealing can be linked to population growth and economic development. However, perhaps the valuation of soil should be linked to its ability to provide ecosystem services, and the implementation of land sealing fees.

Connectivity Raising awareness of decision-makers, planners and residents about the value of soil for creating life quality in urban areas by providing ecosystem services, at the same time underlining the negative consequences of a land management approach with limited protection of soil resources.

Codification The use of land is nearly always a trade-off between various socio-economic and environmental factors, i.e. housing, transport infrastructure, energy production, agriculture, and nature protection (European Commission, 2012). To promote sustainable soil management, various strategies and policies could be adopted, including the implementation of land use and spatial planning approach, i.e. urban growth boundaries setting (Gennaio et al., 2009), and the pursuance of brownfield regeneration.

viii. Habitat loss/degradation. Aside from providing various ecosystem services, soils are habitat for many species. Habitat loss and degradation can be defined as a decline and loss of habitat for both above- and belowground species. In the recent decades, due human activities (i.e. agriculture and urbanisation), habitat loss is occurring at alarming rate. This threat can potentially be linked to the inability of soil to perform its functions.

Capacity Because the interactions between soil biota and soil matrix are fundamental, the loss of habitat for the ground-foraging mammals means a reduced ability to perform ecosystem services. Indicators that contribute to greater food and biomass production (one of the main drivers) could potentially be used, i.e. carbon and pH (buffering).

Condition The habitat loss essentially affects the biodiversity. Hence, any indicators related to habitat biodiversity could potentially be utilised, including tree density and species richness despite that the above ground biodiversity is more widely reported than those below ground (Jeffery and Gardi, 2010). Changes in soil faunal and microbial diversity of phenosoils versus genosoils would be direct indicators of condition.

Capital From the decision maker's point of view, habitat loss can be linked to loss of ecosystem services, which is essentially a negative balance on the natural capital accounting book. Another approach is to introduce the environmental costs (i.e. habitat loss fees) into final products which are shared within producers and consumers.

Connectivity To prevent further disruption in soil, there needs to be a connection between producers and consumers. This could be measured by assessing the accessibility / transparency of the origin of the commodities linked to land degradation and for food production

Codification The implementation of land use planning would assist in reducing habitat loss within the environment.

6.3.3. Summary of threats to soil

By way of a summary a tabulated list of potential indicators and utility graphs for threats to soil for each of the soil security dimensions is presented in Table 3. Once again, this list is indicative and not exhaustive.

7. Modelling approaches

7.1. Selection of a minimum dataset of indicators

In the literature, once a set of potential indicators is defined and samples have been collected, it is common to use numerical methods to further refine the set of indicators, generating what is usually referred to as *minimum dataset* (MDS). For instance, Andrews et al. (2002b) used PCA to select the MDS, discarding correlated and irrelevant indicators for a given function. As Andrews et al. (2002b) reported, the largest limitation of this approach is that the final MDS (and hence the resulting security score) is management and site-specific. This makes the assessment and comparison of the soil security status in space and time challenging.

To address this limitation, we propose the use of a carefully curated MDS. This implies measuring a suite of soil properties that describe soil as an entity. When compiling Tables 1-3, we utilised some 65 unique soil properties that we propose as a starting potential dataset (PDS). Many of these properties are routinely measured or can be predicted using pedotransfer functions and soil spectral calibration models. This set can then be used within our proposed soil security framework or others, such as the comprehensive (global) soil classification system developed by Hughes et al. (2017) which uses a suite of 23 soil properties with a large overlap with our proposed PDS. This PDS also coincides with many of the soil properties used in methods to assess soil quality (Bünemann et al., 2018). These soil properties mostly encompass the capacity and condition dimensions but possibly can be extended to assess the rest of the dimensions. A major difference with previous approaches are the economic, social and policy indicators and the comparison of phenosoils and genosoils for a particular evaluation.

7.2. Transformation of indicators into scores using utility graphs

To easily compare and integrate different indicators, it is necessary to convert them to a common space. In the literature, this is usually done by mapping a soil indicator to a score using a mathematical function (e.g. Andrews et al. (2002b); Volchko et al. (2014)). Here, we reiterate that we refer to such a mathematical function as a "utility graph" to avoid confusion with the more extant "*soil function*". The utility graph represents the relationship between a soil indicator and a target score that depends on the function, service or threat.

The shape of the utility graph will be defined, as a first attempt, by expert knowledge to depict well-known responses reported in the literature. For example, Volchko et al. (2014) use "more is better", "optimum", and "less is better" to describe the general shape. In Table 1-3, we used a similar approach to define four to six general shapes for each indicator, namely "higher is better", "optimum", "less is better", "binary", and "categorical" (Fig. 3; utility graphs).

When multiple scores are available (assuming that they have not been already integrated to generate a utility surface), it is necessary to combine them into a single score. Andrews et al. (2002) used the eigenvalues of the relevant principal components (i.e. with eigenvalues $>$ 1) normalised by their sum to assign a weight to each indicator score, which are then added. We argue that this PCA approach may have been misapplied. Using highly correlated indicators in a PCA overemphasises their contribution to principal components (since they generally end up in the same component), distorting the analysis result (Bernstein et al., 1988; Wasfy et al., 2020). From a dimensionality reduction perspective, this is not a problem, but it can be problematic if the PCA results are used further (Robertson et al., 2001). This is the case in most current

Table 3
Indicative list of indicators and utility graphs for resisting a range of threats to soil for each of the soil security dimensions. (↗) represents an increasing utility graph, (↘) a decreasing one, (∩) a mid-point optimum, (0,1) as binary, and as categorical. The list is illustrative and not exhaustive. Note that some of the utility graphs (↗, ↘) might not exactly follow a straight line relationship, but could potentially be sigmoid (,) or trapezoidal shape(,) based on certain threshold value.

Threats	Capacity	Condition	Capital	Connectivity	Codification
Accelerated erosion	Aggregate stability (↗); soil surface shear strength (↗)	Degree of slope (↘); slope length (↘); ground cover (↗); bulk density (∩)	Avoided cost of erosion (↗)	Collaboration of farmers, government agencies, contractors (↗); research papers across disciplines (↗)	Regulations and incentives to prevent erosion (0,1); policies to restore eroded land (0,1)
Acidification	pH buffering capacity (↗)	pH (∩)	Loss of production (↘); cost of liming (↘)	Implementation of BMP (↗); knowledge of pH optima (↗)	Regulation policy (0,1); liming incentives (↗)
Salinisation	Genosoil EC and ESP (↘); deep drainage (↗)	Current EC (↘); ESP (↘)	Impact on food production cost (↘)	Farmers knowledge (0,1); BMP for irrigation (↗)	Regulations regarding fertilisation and irrigation (0,1)
Decarbonisation	Genosoil's carbon content (↗);	Current carbon content (↗)	Carbon credit offset (↗)	Adoption of agroecological - regenerative agriculture (↗); awareness of produce grown sustainably (↗)	Carbon policies implementation, i.e. Kyoto protocol (↗); presence of carbon market (0,1);
Contamination	Genosoil's biodiversity (↗); CEC (↗)	pH(∩); biodiversity(↗)	Cost of polluted soils and clean up (↘)	Awareness of proper way of disposal for various compounds (↗)	Soil pollution protection act (0,1)
Soil structural decline	Vulnerability to compaction by soil type/ texture class and climatic zone, (↘)	Porosity (↗); carbon content (↗); COLE (linear extendability) (↗)	Amelioration costs (↘)	Knowledge of farmers on trafficability (↗)	Regulations on carbon farming and no tillage practices (0,1)
Soil sealing	Linear shrinkage (↘)	Land use intensity (↘); urban sprawl map (↘); amount of artificial surface (↘)	Implementation of sealing fees (↗); payment for loss of natural resources (↗)	Attitude towards infrastructure development vs ecosystem services (↘)	Regulations on land use planning (0,1); brownfield regeneration (↗)
Habitat loss/ degradation	Genosoil's carbon content (↗); pH buffering capacity (↗); redox poise (↗)	Tree density (↗); soil species richness (↗)	Habitat loss penalties (↗)	Attitude towards food source coming from responsible farmers (↗)	Regulations on land use planning (0,1)

*Categorical level to be determined; Abbreviations. BMP: Best Management Practices; CEC: Cation Exchange Capacity; COLE: Coefficient of Linear Extensibility; EC: Exchangeable Cations; ESP: Exchangeable Sodium Percentage.

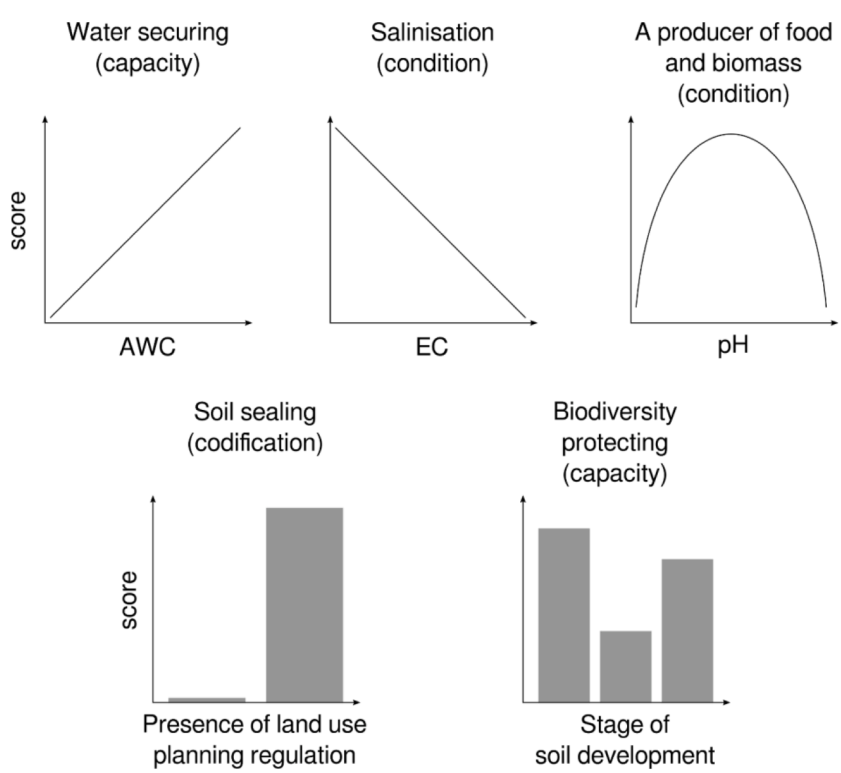

Fig. 3. Examples of utility graphs across various roles and dimensions.

approaches to assessing soil security where highly correlated indicators are not discarded before performing a PCA and the distorted results (eigenvalues and factor loading) are used to assign weights to the different indicators. Since our approach uses a complete suite of indicators, our proposed methods must be able to deal with challenges such as multicollinearity and features with low variance.

7.3. Integration of various security scores

In the literature, most approaches generate a single score that reflects various functions or services (e.g. Calvet-Mir et al., 2012; Mendes et al., 2021), similar to what we consider in the intersection of capacity/condition and functions/services. Our proposal is a highly-granular, integrative framework where we try to define independent scores for each function, service and threat. However, the multiple scores can also be aggregated at different roles and dimensions (Fig. 4) depending on the purpose of the assessment.

Aggregation can be applied to each row and column of our score matrix to obtain poly- and multi-scores, respectively or to the whole score matrix to determine the pluripotency of the soil. At every level of aggregation, the scores can be used to compare two locations or time periods based on their Euclidean (or some other) distance considering their overall security or focusing on specific aspects.

The most straightforward aggregation strategy is obtaining an average score which gives a general overview of the soil security at a specific location or time period. Since actions taken to increase soil security will most likely focus on priority areas, obtaining the minimum score can be another useful aggregation strategy to identify the limiting factor, also avoiding obscuring low-security scores.

It is worth noting that, although illustrative, reducing the complexity of soil security to a single value is not generally recommended. While the different categories were defined by trying to keep them independent from each other, in reality, there are many interactions, and we should move towards a framework that can account for them. In the literature, several lines of work have accounted for interaction between soil functions and could be extended to be used within our framework. Some examples include statistical modelling with Bayesian belief networks (Vrebos et al., 2020), multi-criteria decision modelling (Debeljak et al., 2019), and co-occurrence with correlation studies (Zwetsloot et al., 2020).

An example of multi-criteria decision modelling is the analytical hierarchy process (AHP). The soil security score matrix has been designed from a soil-centric perspective, without considering stakeholders' preferences. In reality, decisions have to be made, sometimes decreasing the security in certain aspects to increase it in others. For example, in general, food production has an implicit cost in terms of soil biodiversity (de Graaff et al., 2019; Tsiafouli et al., 2015). We need to produce food to eat, so, how much biodiversity are we willing to sacrifice? These trade-offs and interactions can be accounted for using AHP. This method is capable of solving a prioritisation problem by assigning different weights to each cell of our soil security score matrix to fit certain purposes. Each stakeholder can assign different weights to each cell of the score matrix which then can be used to combine the security scores. Of course, to successfully apply such an approach it is necessary to gather a diverse group of stakeholders to avoid bias.

8. Discussion

8.1. Should genosoils and phenosoils be a target?

The short answer is it depends, but generally we are interested in learning about soil change and resistance to change. Soil changes through time impacted by human intervention and global change responding to the natural pedogenetic processes. This is captured by the concepts of genosoils and phenosoils. However, the interpretation of soil change can vary from degradation to improvement depending on the intended soil use or management objective. An analysis of the trade-offs and synergies between functions, services, and resilience to threats, and how these vary will benefit from the comparison of phenosoils to their genosoils. Weighing and aggregation methods that incorporate the preferences of different stakeholder groups (e.g., AHP), and the criteria to choose the optimal management scenarios (e.g., all soil functions fulfil a critical performance level, or selected functions are maximised) will influence the assessment, and thus either genosoils or phenosoils can result as the management target. Should there be an overall positive improvement of phenosoils in comparison to the genosoils, then genosoils do not necessarily have to be the target. However, if there is a negative contribution from phenosoils in comparison to the genosoils, management interventions should be implemented to "return" the phenosoil to its original state if possible. If phenosoil cannot be returned to its original state, then in a logical sense this define it as a new genosoil.

8.2. Aggregations

To assess how secure the soil is to support humanity and planetary functioning, evaluation of these approaches needs to be aggregated. There have been many studies focusing on soil multifunctionality (Coyle et al., 2016; Schulte et al., 2015; Zwetsloot et al., 2020). However, there aggregations could be done in various ways, depending on the purpose of the assessment.

		Role			
		Functions	Services	Threats	
Dimension	Capacity				*Poly-capacity*
	Condition				*Poly-condition*
	Capital				*Poly-capital*
	Connectivity				*Poly-connectivity*
	Codification				*Poly-codification*
		Multi-functionality	Multi-serviceability	Multi-threat	**Pluripotency**

Fig. 4. The overall soil security assessment will consider a set of Functions, Services and Threats evaluated for each of the soil security dimensions. Each of the 15 cells in the body of the table represent the appropriate aggregation across dimensions for each role (i.e. red arrow), and across roles for each dimension (i.e. blue arrow). We highlighted an example of aggregation of function over all the dimensions to estimate multi-functionality, as well as aggregation of capacity across all roles to estimate poly-capacity.

8.2.1. Aggregating roles over dimensions

The overall functional delivery of a soil is conditioned upon synergies and trade-offs between functions. How the synergies and interactions between functions vary with land use, climate and soil class is accounted for in the multifunctionality of a soil. Here, multifunctionality refers to the fulfilment of all functions over the five dimensions of soil security.

Similarly, the multitude of services provided by soils is accounted for in the multi-serviceability. These services provided overlap with each other. Hence, there is a need to assess it as a whole, i.e. soil acts as a sink for carbon as part of its climate change mitigation services, but with this service, it potentially affects the water cycle (water securing services) and other services as well. Assessing multi-serviceability is similar to evaluation of the ecosystem services provided by soils.

The multi-threat of a soil refers to the evaluation for each threat to soil each combined over all dimensions. The combination can be estimated via one of several approaches; the most likely of which are the AHP, the minimum or average operator from fuzzy sets. For a multi-threat evaluation, the dimensions are assessed for their resilience to the threat.

8.2.2. Aggregating dimensions over roles

Although *multi-functionality* has previously been estimated (Coyle et al., 2016; Schulte et al., 2015; Zwetsloot et al., 2020), it is not defined in the same way as we propose. Here, we can extend the concept to consider more dimensions than condition and capacity (Fig. 4). So, we can also define and estimate *multi-serviceability* and *multi-threat*. In the same manner, we can aggregate the dimensions across the roles. This gives us a number of previously unrecognised concepts, which here we prefix the term poly- suggesting 'many'. So, we have *poly-capacity, poly-condition, poly-capital, poly-connectivity* and *poly-codification*.

It remains to be seen if these concepts are useful. For example, do the scores which give a soil a high score, for say functions and services, also give a high score for surety (low threats)? Where the scores diverge across the roles does this indicate potential interventions? It will be interesting to see whether poly-codification is possible. The value or deficiency of these concepts will only be revealed when real-world case studies are evaluated.

8.2.3. Pluripotency

Each of the multiple soil functional, soil service and threat to soil combinations can be fused to give a grand assessment. Likewise, a similar evaluation can be made by combining the poly-capacity, poly-condition, poly-capital, poly-connectivity and poly-codification evaluations. Hopefully, the combination of horizontal marginal combinations (multi-) and the vertical marginal combinations (poly-) will yield the same overall aggregation which can be considered a comprehensive view. It will be useful to drill down to highlight the functions, services or threats to soil and the dimensions which are the most limiting to soil security; this will suggest management or policy options for enhancing security.

8.3. Resilience

Resistance contains the notion that the soil through its properties which bestow functionality, service, or threat is difficult to change throughout a disturbance (better termed buffered) whereas resilience refers to the elasticity of capacity to recover, and together inform on the sustainability of a particular use (Williams and Chartres, 1991) through time. The genosoil-phenosoil duality allows us to estimate the magnitude of change and hence the resistance against decline in soil functions and services. Resilience assessments are more difficult to document as they require data from long-term soil experiments (e.g., North American Long-Term Soil Productivity study (Powers et al., 2005)) but can also rely on chronosequence studies after land use abandonment or restoration (Kurganova et al., 2019; Teixeira et al., 2020). Soil resilience depends on soil type, climate, vegetation, land use, disturbance regime, and temporal and spatial scale (Seybold et al., 1999), factors that also influence the functions and services of genosoils and phenosoils. Thus, genosoil and phenosoil comparisons could inform the trajectory and thresholds in soil recovery, with some considerations: presence or lack of hysteresis, the degree of recovery relative to the initial state (pre--disturbance reference), the temporal scale of recovery and required management practices. The presence of tipping points is hypothesised but rarely observed or documented for soil systems (Kuzyakov and Zamanian, 2019). In this proposal, the utility graphs of ability to buffer threats to soil (Table 3) are most related to the resilience of soil properties, whereas the comparison between genosoils and phenosoils across dimensions inform of the resilience of soil functions (Table 1) and services (Table 2). In soil security, resilience can apply not only to condition, but to all dimensions. Resilience of capital, connectivity or codification dimensions are of course more related to economic elasticity and the plasticity of socio-political systems than to the soil itself.

8.4. How to implement the proposal?

The main purpose of this paper is to outline a detailed comprehensive scheme for evaluating soil security. We can imagine an iterative process the first step of which is to apply the outline proposal to a real-world area of interest. An appropriate realistic area might be a small river catchment (watershed) - at least a region with enough pedodiversity that might illustrate different states of the three roles - soil functioning, serviceability, and threats - largely manifested via different classes of soil and land use - so together reflecting different states of soil security. Individual fields or farms are unlikely to demonstrate that level of diversity.

An appropriate sampling approach would be a stratified random design with strata defined by genosoils (soil-forming factors) and further divided into various phenosoils (land-use history), In addition to soil observations a range of stakeholders (inter alia landholders and managers, local authorities and communities, NGOs) interested in the security of the soil within the area of interest would have to be recruited. Their role is to evaluate success and to refine scoring functions and to help assess weights for multi-attribute combination (e.g., by AHP). A sampling design for their recruitment also needs to be considered.

Success of the evaluation system may be assessed by a number of factors including:

1 Some biophysical modelling for the capacity and condition dimensions
2 Economic modelling for the capital dimension
3 Stakeholder agreement for the connectivity and codification dimensions
4 Sensitivity or redundancy of indicators
5 Time taken to complete the process
6 Ability to suggest ameliorative measures

This would then feedback into a new version of the indicators, scoring functions, weights etc. When the framework is stable then an appropriate digital tool for its application can be assembled. Finally, at this stage we have chosen not to add 'soil ecosystem services' as a separate role because i) there is a large number of soil ecosystem services, ii) work is needed to measure and quantify many of them, and iii) they are potentially possibly expensive to measure. As the science of soil ecosystem services clarifies, we may be able to add this category as a fourth role.

9. Conclusions

- In the assessment of soil's ongoing value to humanity and planetary functioning many overlapping concepts have been developed, but all are to some extent incomplete. Here we purposefully attempt a more systematic and thorough assessment.

- Soil functions, soil services and threats to soil are three roles of soil to consider concomitantly to gauge the ongoing ability of a soil to support humanity and planetary functioning.
- For each of the fifteen intersections of the five soil security dimensions and the three roles, we propose an indicative (and admittedly inexhaustive) set of indicators and utility graphs to assess soil security.
- Previous approaches to quantification and aggregation have been constrained by the context of the applications which make them difficult to compare as they involve some arbitrary definitions. We suggest new systematic, algorithmic, and objective methods which are transferable across time and space.
- We recognise various modes of aggregation beyond multi-functionality, e.g., multi-service and poly-capacity.
- We have proposed a generic approach to, and outline framework for, soil security evaluations which should now be tested and improved in real-world situations locally and regionally.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgement

We acknowledge the support of the Australian Research Council Laureate Fellowship (FL210100054) on Soil Security entitled ‘A calculable approach to securing Australia’s soil’.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.soisec.2023.100086.

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