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Discussion

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ABSTRACT

Soil health is a key concept in worldwide efforts to reverse soil degradation, but to be used as a tool to improve soils, it must be definable at a policy level and quantifiable in some way. Soil indicators can be used to define soil health and quantify the degree to which soils fulfil expected functions. Indicators are assessed using target and/or threshold values, which define achievable levels of the indicators or functions. However, defining robust targets and thresholds is not a trivial task, as they should account for soil, climate, land-use, management, and history, among others. This paper introduces and discusses (through theory and stakeholder feedback) four approaches to setting targets and thresholds: fixed, reference, distribution and relative change. Three approaches (not including relative change) are then illustrated using a case study, located in Denmark, Italy, and France, which highlights key strengths and weaknesses of each approach. Finally, a framework is presented that facilitates both choosing the most appropriate target/threshold method for a given context, and using targets/thresholds to trigger follow-up actions to promote soil health.

1. Introduction

1.1. Background to setting targets and thresholds

Soils contribute to a wide range of ecosystem services (FAO/ Intergovernmental Technical Panel on Soils, 2020; Veerman et al., 2020; Ecdgri et al., 2021). Within the Common International Classification of Ecosystem Services - CICES (Haines-Young and Potschin-Young, 2018), one-third of the 83 ecosystem services (defined in version 5.1) are directly controlled by soils and their associated properties, while more than half are indirectly affected through agricultural soil management (Paul et al., 2021). Even though soil management practices are changing around the world, past practices have too often had negative effects on soil functions and properties (e.g., erosion, compaction, soil sealing,

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contamination, etc.) (Stolte et al., 2015), leading to uncertainty about the long-term ability of soils worldwide to continue supporting and delivering ecosystem services. Globally, at least 33% of all croplands are moderately or highly degraded, with this proportion increasing when considering croplands where external inputs, such as fertilizers and pesticides, or new plant varieties, are masking the impact of degradation processes (FAO and ITPS, 2015). In the EU, across all land uses, it is currently estimated that 61% of soils are affected by soil degradation (EUSO, 2023).

At the centre of the current effort in Europe to reverse soil degradation is the concept of soil health. Soil health is a valuable metaphor which connects soil-related human activities to a healthy society and healthy people (Harris et al., 2022; Panagos et al., 2022). However, to be used in practice, soil health must be definable at a policy level and quantifiable in some way. Soil health indicators are measurable soil properties or functions, which can indicate the degree to which soils can fulfil expected ecosystem services (Lehmann et al., 2020). While a set of simple, generic soil health indicators would be helpful for policy and governance, identifying such a set is not a trivial task (Bünemann et al., 2018), as the role of soils in ecosystems is complex (Paul et al., 2021; Smith et al., 2021). Relevant indicators for soil health may also differ depending on the context. National and EU-wide monitoring require a small set of indicators, simply for reasons of cost limitation (Faber et al., 2013). For farm or regional decision support and monitoring, stakeholders may use more extensive data, tailored to ecosystem types and land uses. These differences could be addressed in a tiered system, where a basic set of indicators is followed up by increasingly specialized additional indicators, which can be triggered when existing information is insufficient to satisfactorily inform decision-making. For EU-wide soil monitoring, this approach was first proposed in 2006 (Van-Camp et al., 2004; Huber et al., 2008), and again in 2021, as a structure to link national monitoring with smaller-scale assessments (Faber et al., 2022). However, a functional tiered system requires, for each of those scales and within the context of ecosystem type and land use, target and/or threshold values to define achievable soil health, within which a soil can sustainably function and deliver ecosystem services (Faber et al., 2022).

1.2. Four approaches to setting targets and thresholds

Each soil health assessment will have a specific context and purpose, which will inform which indicators are used and how indicators are assessed. The choice of soil health indicators may include single soil properties and/or soil functions. For some soil health assessments, both targets and thresholds may then be defined for those indicators, whereas for others only one (a target or threshold) may be meaningful or necessary. Indicator choice and the context-specific considerations for assessing indicators are not within the scope of this paper. Here, approaches to setting 'targets and thresholds' are broadly discussed with the understanding that context matters and that soil knowledge will be required in order to assess targets/thresholds relative to function within different contexts. For the purpose of this paper, a ***target*** is defined as an indicator value desirable to reach (i.e., a known limit or achievable value), while a *critical* ***threshold*** is the 'minimum criteria,' an indicator value above/below which soils are targeted as needing intervention, without implying that soils that meet these criteria are in a good state. Note that, while not specifically addressed in this paper, a ***range*** (i.e., defined upper and lower values) can also be used as a broad target, or as a set of critical thresholds.

The *'fixed' approach* is the most frequently used; fixed values for targets and thresholds are ideally developed from direct, objective observations under well-defined conditions (soil type, climate, geology, etc.). A threshold for aluminum, for example, could be $pH_{water} < 5.5$, when plant-available Al cations are released to soil solution and become potentially toxic to plants (Rahman and Upadhyaya, 2021). The same occurs for trace elements where limits in soils can be set to avoid toxic effects on soil biota or bioaccumulation. In such cases, the threshold reflects a direct causal relation (or sufficiently confident correlation), which can be drawn between a key soil function and indicator value. However, for an indicator like soil organic carbon (SOC), related to multiple soil functions (Johnston et al., 2009; Terrat et al., 2017; Begill et al., 2023), setting a unique value is challenging because the quantitative evidence for such thresholds is lacking (Loveland and Webb, 2003). Fixed values may also be set pragmatically, such as setting an upper threshold for eroded soil of 1 t ha^{-1} yr^{-1} (Verheijen et al., 2009), based on the consideration that soil erosion losses are tolerable if less than or equal to the rate of soil formation (Soinne et al., 2016). In the case of SOC, a pragmatic target could be, as in Table 2.5 of EEA (2023), the level at which further accumulation of OM may lead to trade-offs, such as nitrate losses. However, thresholds may also be set to target soils most in need of intervention. Panagos et al. (2015) proposed a 2-t ha^{-1} yr^{-1} erosion threshold for future soil protection measures and the proposal for the Soil Monitoring Directive (Commission, 2023) also considered this to be an appropriate threshold for healthy soils.

The *'reference' approach* compares indicator data in the region/soils of interest to a reference situation, where soil processes are occurring in a way that is considered to be a desirable goal. The definition of *desirable* can be any aspect of soil health or ecosystem service delivery that is considered a priority, but ideally also accounts for ecosystem service trade-offs (i.e. Ndong et al., 2021). The reference approach is based on the recognition that soils under native vegetation, such as permanent grassland, exhibit better health, for example in terms of nutrient cycling, carbon content, biodiversity and/or water infiltration than their cropped counterparts (Maharjan et al., 2020; Das and Maharjan 2022). By extension, soils that are not intensively managed (such as pastures for grazing), may also have processes occurring in a way that reflect a maximum potential for agricultural soils. For example, in setting baselines for biological groups, Cluzeau et al. (2012) showed that meadows in Brittany have consistently higher biological abundance and richness than croplands in the same region. While croplands may not be able to fully achieve the level of indicators observed in less intensively-managed soils, the reference situation can act as a standard for setting targets. Sparling et al. (2003) used 80% of the SOC stocks under permanent grassland as a target for New Zealand croplands, and used the CENTURY model to set a threshold, based on the point at which the soil could recover SOC stocks to the target value within 25 years of implementing permanent grassland.

In the *'distribution' approach*, indicator data is assessed within a population (stratified by soil type, land use, climate, etc), and the distribution of data is used to generate targets and thresholds defined as a certain percentile of that distribution. This data-driven approach was used to identify SOC targets in France, and authors noted that while it is sensitive to the percentile chosen, this provides flexibility, allowing targets to be set based on the criteria of different stakeholders (Chen et al., 2019). In the Netherlands, the distributions of multiple soil indicators (mostly biological) were used to identify 'ideal references sites', essentially combining the distribution and reference approaches, by reporting the means from ideal locations as well as the upper and lower percentiles of the complete distribution (Rutgers et al., 2008). A multi-indicator webtool (including pH, organic matter, bulk density, and earthworm abundance) for the United Kingdom uses the distribution approach to allow users to see where their data sits within a population of similar soils (Feeney et al., 2023), but authors note that values in the highest and lowest percentiles require further investigation. In this sense, the distribution can be used for continual improvement, allowing stakeholders to identify the best performers and learn from their management. Similarly, Drexler et al. (2022) concluded that distributions are easy for stakeholders to understand but cautioned that it was not always possible to link soils above/below defined benchmarks to best/unfavourable management practices. Such approaches based on the distribution of soil parameters were also used to develop scoring functions to compare and assess soil health at a regional level in the USA (Fine et al., 2017; Nunes et al. 2021, 2024) depending on soil type and climate.

The *'relative change' approach* is based on the current local soil condition. The target (though more accurately 'benchmark', defined in this paper as a fixed-term point of reference, in contrast to long-term targets or thresholds) is defined as an increase or a decrease of a certain percentage of the current value within a specified number of years. This approach is based on the understanding that the setting of targets and thresholds is meant to facilitate an improvement in soil health, irrespective of the gap between current values and potential values. Therefore, a long-term target or threshold may not always be required, if information on the current soil status is available, as well as an understanding of the desired direction of change. At a local scale, the "4 per mille initiative" launched at the 2015 United Nations Climate Change Conference (COP 21) is an example of such a relative change expected to improve soil health and contribute to climatic change attenuation and mitigation (Minasny et al., 2017). On a larger scale, this is also the approach used by the European Commission, who, given a baseline of 60–70% of soils being unhealthy in 2020, set the target of 75% of soils being healthy by 2030, a 100% relative change (Veerman et al., 2020).

1.3. Advantages and disadvantages of the four target/threshold approaches

Each of the four approaches to setting targets and thresholds has advantages and disadvantages (Table 1). Using a fixed (researched, published) target would be the simplest approach, but given the need to stratify targets and thresholds by climate, soil, land use and management criteria (EEA, 2023), as well as other context-specific requirements, the knowledge required to assign robust, fit-for-purpose targets and thresholds is simply not available in many cases. It is also notable that data is associated with a specific analytical method (e.g., pH measured in water or $CaCl_2$ or KCl); even when fixed values are available, it may not be possible to apply them in all countries. The most significant drawback to the reference and distribution approaches is the arbitrary nature of assigning percentages or percentiles (i.e. Sparling et al. (2003) clearly state that their assigned target of 80% SOC is arbitrary). The reference approach also requires the selection of an appropriate area or situation to act as a reference, where the soil has a meaningful/achievable value of the indicator as compared to an agricultural soil. Methods have been proposed e.g. by crossing climate, soil and land cover information (Das and Maharjan, 2022), yet it remains difficult to identify proper reference situation or areas. The distribution compares a population of soils with itself, removing the need for a separate reference, but targets and thresholds remain subjective and are highly sensitive to skewed distributions if soils in the area are degraded. The relative change approach has many advantages for simplicity, at least at farm scale: no stratification, no extensive knowledge, large data sets or reference situations required, and the choice of analytical techniques is open, assuming that consecutive measurements are done using the same technique. The weakness of the approach is that while it supports soil health improvement through a series of fixed-term benchmarks, it has no clear end point, and cannot provide explicit information on whether soil health status is good enough.

1.4. A framework for setting targets and thresholds

Faber et al. (2022) conducted a review of existing soil targets and thresholds used in EU countries, which showed that except for nutrients (e.g., nitrogen, phosphorus) and contaminants (e.g., trace elements), such values are not currently widely used nor actively developed. A recent European Environmental Agency (EEA) report (EEA, 2023) provides an overview of the challenges in setting targets and thresholds, noting that these are highly site-, management- and climate-specific, and that careful validation in each resulting category would be critical to fully support any given target or threshold system. With policies being established worldwide to promote sustainable land use and ecosystem health, there is an urgent need for the rapid development of targets and thresholds to assess soil health. Moreover, soil data evaluation should be undertaken within a harmonized framework, using targets and thresholds that are systematically derived in comparable ways, but can arrive at both national- and region-specific values. This paper presents four different target and threshold-setting approaches, exploring stakeholder perception of the approaches, as well as their practical use through a case study of one soil health indicator across different locations in Europe. The results are then used to develop a flexible framework for setting and using targets/thresholds in a soil health assessment.

Table 1
An assessment of advantages and disadvantages associated with four different approaches of setting targets and thresholds for soil health indicators.

Approach	Definition	Advantages	Disadvantages
Fixed	Static value based on best available research/ knowledge, stratified as required	A quick way to start assessing at a large scale, can be used at field scale and is simple to understand for practitioners.	Needs stratification, there is a lack of knowledge at the level required to adequately stratify (soil, climate, land-use, management, history, etc.)
Reference	Static value, calculated as a percentage of what would be found in a reference situation, where soil processes are occurring in a way that is considered to be desirable, stratified as required	Given an appropriate reference, provides an approach to establish a value; a single value is simple to use for practitioners.	Needs stratification, many indicators/ regions will not have an appropriate reference. Criteria to decide percentage is arbitrary and difficult to explain.
Distribution	Changeable value, based on the regional state of the soil (i.e., target/threshold defined as a certain percentile of the current observed range of values), static only until distribution is re-measured, after which the target/ threshold may change	Provides an approach to establish a region and land-use specific value, can be useful for practitioners to see how they compare to others in the sense of developing continual improvement.	Needs stratification, dedicated sampling to get unbiased estimate of the statistical distributions, distribution will be skewed if area is already degraded, criteria to decide percentiles is arbitrary and difficult to explain.
Relative change	Changeable value, based on the local state of the soil (i.e., target defined as an increase or decrease of a certain percent within a specified number of years), static only for stated time span, after which the soil is re-measured, and the target will change	Provides a quick way to start evaluating trends, highly situation-specific (no stratification required), takes starting point into account.	May be problematic for land managers who are already doing well, may not be applicable for mapping if there is a high uncertainty with respect to changes, may require at national level the implementation of a robust monitoring network.

2. Materials and methods

2.1. Stakeholder feedback on target/threshold approaches

The four approaches (fixed, reference, distribution, relative change) to setting targets and thresholds were presented during two online EJP SOIL Policy Forum meetings, in which participants from policy, consultancy, industry and science participated in knowledge exchange and discussion. The first meeting, titled "EJP SOIL Scientific Support for the EU Soil Health Law", was held on March 8, 2023, and aimed to present scientific information in support of the policy needs for development of the EU Soil Health Law based on research findings of the EJP SOIL program. The event was attended by approximately 100 people from 64 institutes and 19 EU countries. The second meeting, entitled 'Soil Health Indicators – an open webinar' (EJP SOIL, 2023), was held on May 12th' 2023. This webinar was widely promoted within and outside of the EJP SOIL consortium, with the purpose of further increasing access to scientific knowledge provided by EJP SOIL on the topic of soil health indicators and approaches to classify and prioritize indicators. The webinar had 463 participants from 267 organizations and 57 countries around the world. As part of each meeting, participants were asked for their views on soil indicators and approaches to setting targets, using an anonymous, online, audience response system (Mentimeter). During the March meeting, 72 attendees participated in the online questions, while during the May meeting, 263 attendees participated in the online questions.

2.2. Case study

A case study was used to further explore potential advantages and disadvantages of using the different approaches to set target and thresholds. The chosen parameter for the case study was SOC, as it is the most commonly-used parameter in the assessment of soil health (Bünemann et al., 2018; Faber et al., 2022). The case study focused on agricultural soils (cropland and grassland/pasture [hereafter all referred to as grasslands]), and used existing data (from one point in time) to set and visualize targets and thresholds for SOC using the fixed, reference and distribution approaches. This methodology excluded the relative change approach, as it, by definition, requires measurements (or forecasted models) of two points in time. Given the importance of context-specific variations, the case study was located in three different countries (Denmark, Fig. 1; Italy, Fig. 2; France, Fig. 3), which represent a range of pedoclimatic conditions in Europe. In Denmark and Italy, a model-based approach was used, in which spatial estimates of SOC were based on validated models. In France, a design-based approach was used, in which sampling units were selected randomly and statistical estimates (with confidence intervals) of SOC were generated without the use of a model (Brus, 2022).

Note that the purpose of the case study was not to choose the best target or threshold approach for assessing SOC in each region, but to

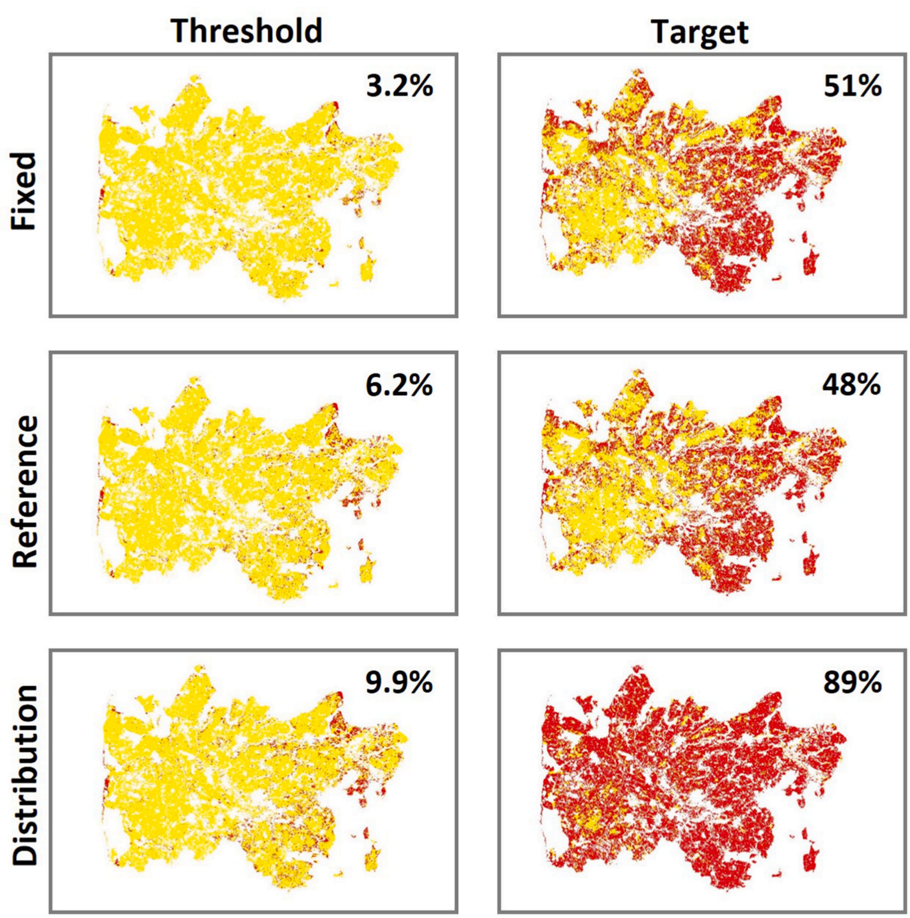

Fig. 1. Maps of Middle Jutland, Denmark, showing agricultural soils (cropland and grassland) where three different approaches for setting targets and thresholds of soil organic carbon (SOC) have been applied: Fixed, Reference and Distribution. Soils above (yellow) and below (red) the target/threshold are shown in each panel, as well as the percentage of land area below the target/threshold (indicated by the percentage in the upper-right corner of each panel). Reference values were based on 50% and 80% of mean estimated SOC values from grasslands in the region. Distribution-based thresholds and targets were derived from the 12.5th and 87.5th percentile of SOC values by land cover and soil texture class. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

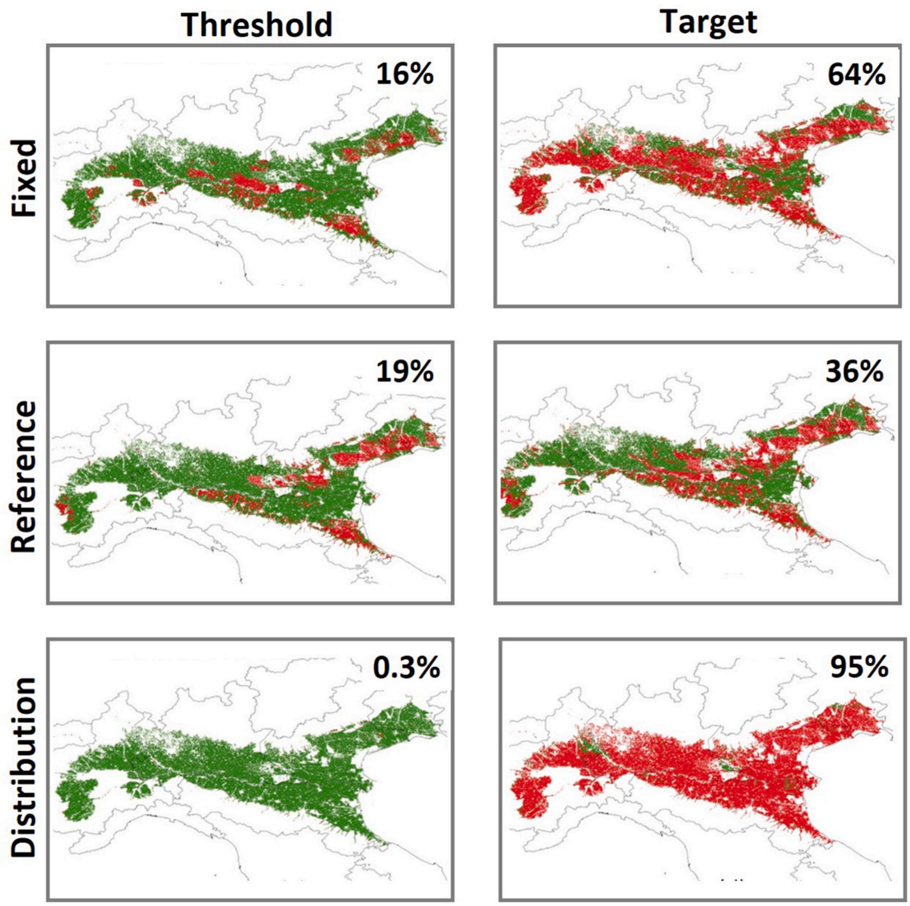

Fig. 2. Maps of Po Valley, Italy, showing agricultural soils (cropland and grassland) where three different approaches for setting targets and thresholds of soil organic carbon (SOC) have been applied: Fixed, Reference and Distribution. Soils above (green) and below (red) the target/threshold are shown in each panel, as well as the percentage of land area below the target/threshold (indicated by the percentage in the upper-right corner of each panel). Reference values were based on 60% and 80% of mean estimated SOC values from grasslands in the region. Distribution-based thresholds and targets were derived from the 12.5th and 87.5th percentile of SOC values by land cover and soil texture class. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

explore the use of the approaches in different locations, to highlight general advantages and disadvantages associated with each approach. Fixed thresholds and targets for all three countries were selected from Table 2.5 in EEA (2023), which is based on data from Germany (Wessolek et al., 2008) and considered valid for Germany and neighbouring countries. The table provides SOC values stratified by soil texture and climatic water balance during summer. At each case study location, data was stratified by soil texture, but the most appropriate climatic water balance was selected for the whole region. The reference thresholds and targets were calculated as 50–60% and 80%, respectively, of the mean estimated SOC values in agricultural grasslands. Distribution-based thresholds were calculated as the 12.5th percentile and targets as the 87.5th percentile for the distribution of comparable soils. Comparable soils were defined as distributions stratified by soil type and agricultural land use (cropland or grassland). Note that both the percentages (reference approach) and percentiles (distribution approach) were chosen arbitrarily as in Sparling et al. (2003).

2.2.1. Denmark: Middle Jutland

Middle Jutland covers an area of approximately 13,000 km^2, just over 30% of Denmark's total land area. The climate is predominantly Atlantic North (Metzger et al., 2005) with a mean annual temperature of 9.0 °C and mean yearly precipitation of 800 mm (reference years 2011–2020) (DMI, 2024). Historically, the landscape consisted primarily of closed-canopy deciduous forest (Rasmussen, 2005), but 63% of Middle Jutland is now dedicated to agriculture and less than 16% remains under forest cover (Statbank, 2023). The landscape consists of Weichselian moraine on calcareous tills towards the east and glaciofluvial plains created by glacial melting towards the west (Appendix A), with the boundary between the two following the maximum extent of the Weichselian ice sheet (Houmark-Nielsen, 1989; Greve et al., 2022). Consequently, the dominant soil types are Podzols to the west of this boundary and Luvisols with a minor component of Cambisols to the east (Adhikari et al., 2014b). That divide also correlates with the predominant agricultural activity; the central and western portions of the region are dominated by cattle in grass-arable rotations on sandy and loamy-sand soils, while intensive arable farming on loamy and sandy-loam soils dominates in the east.

Modelled SOC data (Adhikari et al., 2014a), stratified by soil type (Madsen et al., 1992) and land use (Levin and Gyldenkærne, 2022), was used to generate the Middle Jutland maps (Fig. 1). The EU Commission defines permanent grassland as land 'that has not been included in the crop rotation of the holding for a duration of five years or longer' (Commision Regulation, 2009). That was problematic in Denmark, as most dairy pastures and managed grasslands are in ley-arable crop rotations (Søegaard et al., 2002; Vertès et al., 2007) and conversion to and from medium-term rotations is common (Levin and Gyldenkærne, 2022). Therefore, grasslands in this case study were defined as areas that had been under grassland for more than five years between 2011 and 2021. Fixed values (EEA, 2023) in Middle Jutland were assigned using a

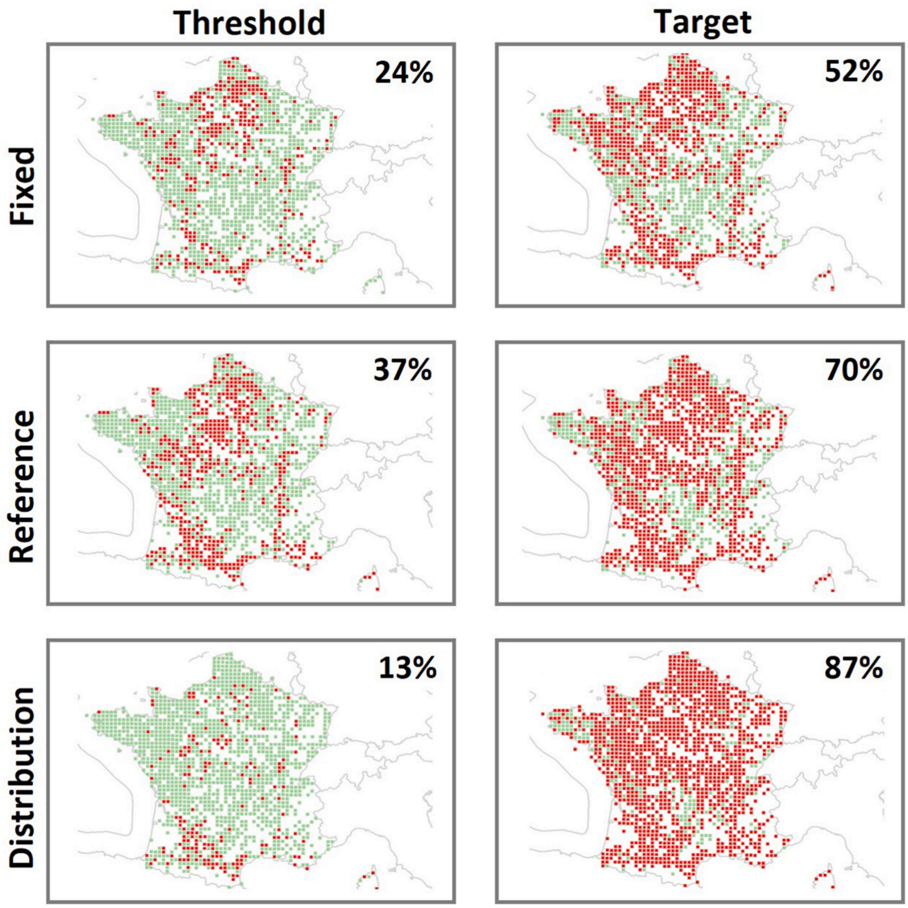

Fig. 3. Maps of France, showing agricultural soils (cropland and grassland) where three different approaches for setting targets and thresholds of soil organic carbon (SOC) have been applied: Fixed, Reference and Distribution. Soils above (green) and below (red) the target/threshold are shown in each panel, as well as the percentage of land area below the target/threshold (indicated by the percentage in the upper-right corner of each panel). Reference values were based on 50% and 80% of mean estimated SOC values from grasslands in the region. Distribution-based thresholds and targets were derived from the 12.5th and 87.5th percentile of SOC values by land cover and soil texture class. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

summer climatic water balance between −100 and 0 mm. Point data from the Danish Soil Classification database (Madsen et al., 1992) was used to calculate the targets and thresholds for the reference and distribution approaches (number of cropland samples = 3658 sand and 5421 loam/clay; number of grassland samples = 548 sand and 424 loam/clay). For the reference approach, the mean SOC of grasslands (grasslands as defined above) was calculated, stratified by soil type. In the distribution approach, soil observations stratified by soil type and land use were used to obtain the 12.5th and 87.5th percentiles.

2.2.2. Italy: Po valley

Italy is characterised by a wide variety of pedo-landscapes, which leads to a remarkably high pedo-diversity (Costantini et al., 2013a,b). From the soil map of Italy (Costantini et al., 2012), the agricultural land (35,795.25 km^2) of the soil region *"18.8 - Po plain and moraine hills of Piedmont and Lombardy"* was selected, due to the intensive agricultural use and elevated risk of SOC loss in the region. The climate is Mediterranean suboceanic to subcontinental (Finke et al., 1998; Costantini et al., 2013a,b) with annual means of 13.5 °C air temperature, 800 mm precipitation and 920 mm evapotranspiration. Soils in this region are widely diverse (Appendix A), with all types of soil texture classes and including Cambisols, Luvisols, Calcisols, Vertisols, Gleysols and Arenosols (Histosols and Phaeozems are also present, but rare) (Costantini et al., 2013a,b).

The soil dataset used was the probability distribution map of the Italian Soil Typological Units (STU) and corresponding Derived Soil Profiles (DSP) (1,109,672 points, 500 m grid) produced by Fantappiè et al. (2023) by neural network. This map was produced using the soil geodatabase developed and maintained by the Council for Agricultural Research and Economics (CREA), which groups different soil data sources, each one with a different soil sampling strategy. To produce the map, the most probable World Reference Base (WRB) Reference Soil Groups (RSG), WRB qualifiers, and USDA textural soil types were mapped on the 500 m grid by neural network. For the Po Valley, 3872 observed soil profiles were used, which were grouped into 246 STUs. The SOC and texture (Schoeneberger et al., 2012) data was based on the topsoil 'functional horizons' of each STU. The resulting map ("SuoliCella500" (Fantappiè et al., 2023);) is shown in Appendix A. The STUs of agricultural land (including cropland, grassland and pastures, excluding forests) were used. The fixed values were assigned for a summer climatic water balance less than −100 mm. The reference values were calculated based on grassland and pasture for each STU (excluding cropland). For some STUs it was not possible to determine a reference value, because those STUs were constituted only by cropland soils. Only 0.15% of the Po Valley is used as permanent grassland (defined as permanently used for forage and not under rotation). The distribution approach was applied by considering only WRB-RSG criteria (excluding WRB Qualifiers and USDA textural soil types), calculating the specific percentiles of SOC in the obtained great groups of STUs, and then the mean SOC content of the STU topsoils was compared to those values. We note that there were STUs present in the Po Valley group soils which were also located outside the valley, but were grouped under those STUs given their classification.

2.2.3. France: national

Mainland France is about 543,965 km^2 and the pedo-diversity here is one of the largest in Europe and the world (Minasny et al., 2010; Arrouays et al., 2022). Landscapes vary from coastal plains with low elevation in the south-west and north, to the mountainous areas in the south and east. Average annual temperatures increase from north to south, but temperatures decrease with altitude, while precipitation increases with altitude. The climate ranges from Mediterranean in the south, to temperate oceanic in the north, and tends to be semi-continental further away from the Atlantic Ocean. Climate, landscape, and geology have resulted in a heterogeneity of soils. The major soil types are Cambisols and Luvisols, covering 37% and 17% of the country, respectively (Appendix A). Soil types are influenced locally by vegetation and land use, resulting in major differences in SOC across France (Martin et al., 2011). All soil textures are present in in France, with the general pattern of sandy soils being located in the southwest, silty soils in the northern part of the country and some clayey soils in the east and southwest.

Using the Institut National de la Recherche (2021) dataset, from the French systematic soil quality monitoring grid (RMQS) (Arrouays et al., 2002; Jolivet et al., 2022), design-based estimates (Brus and Saby, 2016) of the proportion of French area under or above a specific threshold were estimated. A total of 2145 sampling sites are included in the RMQS and for each site, the analysis of soil properties is done on a composite sample which is made by mixing 25 sub-samples collected in a 400m^2 area at 0–30 cm depth (Jolivet et al., 2022). Of those 2145 monitored sites in France, 68% (1457 sites) were retained to test the three different approaches, of which 64% were cropland (i.e. 932) and 36% were grassland (i.e. 525; permanent grassland was defined as having been grassland for at least 6 years previous to sampling). Fixed values were based on a negative water balance in summer less than −100 mm (valid across France except in some regions in the mountains). The reference targets were based on the mean value of SOC from grasslands based on the national dataset (Institut National de la Recherche et al., 2021), stratifying by soil type. The same dataset was used for the distribution approach, stratifying data by soil type and land use.

3. Results

3.1. Stakeholder feedback on target/threshold approaches

As shown by the results of the poll questions related to setting targets and thresholds (Table 2), stakeholder perception was largely consistent between the two webinars. Although there was some overlap in participants between the two meetings, many more researchers (85% of participants) attended the meeting on May 12th, as compared to March 8th (53% policy/47% research), so the relative number of policy and research participants differed. The ‘fixed’ approach, which is currently the most widely used, was not seen as a feasible system by most participants (58% on March 8th, and 65% on May 12th). The relative change approach was considered the most feasible approach by both audiences. The reference approach (referred to as the ‘relative to natural’ approach in these webinars) was selected as the *preferred* approach in March, with the relative change approach as the next most popular choice. The question asking for a preference was refined for the meeting in May, by distinguishing between the most *feasible* and most *desirable* reference systems. Interestingly, the two most popular choices in May were the same as the preferred approaches in March, but they were clearly separated by feasible (relative change) and desirable (reference).

Table 2
Stakeholder views on approaches for setting targets and thresholds for soil health indicators. Results are from anonymized polls (Mentimeter) of participants in online meetings on March 8 and May 12, 2023.

Question	Date	Response (% of voters)			
		Yes		No	
Are ***fixed targets*** a feasible reference system for EU/ national/soil district level?	March 8	42		58	
	May 12	35		65	
Are ***relative to natural targets*** a feasible reference system for EU/ national/soil district level?	March 8	68		32	
	May 12	66		34	
Are ***distribution targets*** a feasible reference system for EU/national/ soil district level?	March 8	59		41	
	May 12	81		19	
Are ***relative change targets*** a feasible reference system for EU/national/ soil district level?	March 8	71		29	
	May 12	82		18	
		Fixed value	***Relative to natural***	***Distribution***	***Relative change***
What reference system do you ***prefer*** for EU/ national/soil district level?	March 8	12	45	12	31
What reference system do you think is ***most feasible*** for EU/ national/soil district level?	May 12	8	22	20	50
What reference system do you think is ***most desirable*** for EU/ national/soil district level?	May 12	10	48	16	27

3.2. Case study locations

In Denmark (Fig. 1; Table 3), the fixed approach resulted in 3.2% of the Middle Jutland soils being under the threshold and 51% under the target. With the reference approach, 6.2% of agricultural soils were under the 50%-SOC threshold, while 48% were under the 80%-SOC target, primarily in loamy soils towards the east, in both cases. For the distribution approach, 9.9% of soils were under the critical threshold value, also primarily in the east, while 89% were below the target. The Danish thresholds were consistent with known limits, falling within the range (1–2% SOC) in which tilth-related structural properties have been found to transition between satisfactory and poor (Schjønning et al., 2007).

In Italy (Fig. 2; Table 3), the fixed approach resulted in 16% of the Po Valley cropland soils being under the threshold values, and 64% under the target values. With the reference approach, 19% of the agricultural soils were under the 60%-SOC threshold and 36% under the 80%-SOC target. For the distribution approach, 0.3% of agricultural soils were under the critical threshold value, while 95 % were below the upper target. To explain these percentages obtained with the distribution method, refer back to the description of the methods; there were STUs present in the Po Valley group soils which are also located outside the Po valley.

In France (Fig. 3; Table 3), the fixed approach resulted in 24% of the

Table 3
Soil organic carbon (SOC; g C 100^{-1} g^{-1} soil) targets and thresholds for agricultural soils and respective areas impacted in Denmark, France and Italy, set using three different approaches: fixed, reference and distribution.

Country	Measurement	Soil type or land use	Target-/Threshold-setting approach							
			Fixed		Reference		Distribution			
			Threshold[a]	Target[a]	Threshold[b]	Target[b]	Threshold[c]		Target[c]	
							Cropland	Grassland	Cropland	Grassland
Denmark	SOC target/threshold (g C 100^{-1} g^{-1} soil)	Sand	0.9	1.73	1.06	1.70	1.13	1.10	3.02	3.41
		Loam/clay	0.9	1.92	1.14	1.83	1.26	1.35	2.73	3.44
	Land area below target/threshold	Cropland	2.9%	52%	5.8%	48%	9.1%		89%	
		Grassland	5.5%	45%	8.5%	42%	14%		84%	
Italy	SOC target/threshold (g C 100^{-1} g^{-1} soil)	Sand	0.5	1.23	0.74	0.99	0.43	0.63	2.05	3.25
		Silt	1.5	2.53	0.96	1.28	0.73	0.77	2.29	3.64
		Loam/clay	0.6	1.47	0.92	1.22	0.71	0.75	2.32	4.01
	Land area below target/threshold	Cropland	16%	64%	20%	36%	0.3%		95%	
		Grassland	1%	34%	4.1%	39%	0.4%		85%	
France	SOC target/threshold (g C 100^{-1} g^{-1} soil)	Sand	0.5	1.23	1.15	1.84	0.65	1.08	2.13	3.37
		Silt	1.5	2.53	1.42	2.28	0.90	1.43	2.31	4.25
		Loam/clay	0.6	1.47	1.80	2.88	1.08	2.14	3.04	5.49
	Land area below target/threshold	Cropland	33%	66%	52%	85%	13%		87%	
		Grassland	6.3%	27%	10.7%	44%	13%		87%	

[a] Targets and thresholds were taken from the results of Wessolek et al. (2008), summarized in Table 2.5 of EEA, 2023.
[b] Threshold calculated as 50% (Denmark, France) or 60% (Italy) of the grassland SOC content; target calculated as 80% of the grassland SOC content.
[c] Threshold and target calculated as the 12.5th and 87.5th percentile, respectively.

French agricultural soils being under the threshold values, including 33% of croplands and 6.3% of grasslands under the fixed threshold values. By texture, 47.4% of silt soils were under the threshold values, as compared to 1.9 and 1.3 % of the sandy and loamy soils, respectively. A total of 52% of French soils were under the fixed target values, including 66% of croplands and 27% of grasslands. As for fixed threshold results, 80% of silty soils were under the fixed target value compared to 36% and 19% of sandy and loamy soils. With the reference approach, 37% of the soils were under the 50%-SOC threshold and 70% of the soils were under the 80%-SOC target. Specifically, 52% of croplands and 10.7% of grasslands are under the "reference" threshold value. Silty soils had a 10% higher proportion of soils under both reference threshold and target values compared to sandy and loamy soil classes. Finally, due to the design-based approach applied in France, 13% of soils were under the critical threshold value for the distribution approach, while 87% were below the target.

4. Discussion

4.1. Case study highlights of advantages/disadvantages of the three approaches

In Denmark and France, the three approaches resulted in different percentages of the total land area falling under the target/threshold, yet each approach identified the same general regions, simply with more or less of the soils identified as at-risk (Figs. 1 and 3). In contrast, the fixed and reference thresholds in Italy identified a similar percentage of land area (16–19%), but not always the same regions (Fig. 2). This difference was largely due to silt soils. The fixed-approach threshold for silt soils was higher than the fixed *target* for other soil textures, and also higher than both threshold and target values from the reference approach in Italy. Interestingly, Wessolek et al. (2008) also notes that the values for silt soils are uncertain and would require further verification. As both Italy and France exhibit a much higher percentage of silt soils as at-risk than other soil types, a re-examination of those thresholds seems prudent. Another possibility is that the fixed threshold was a poor fit due to climate, particularly in Italy. As described in the EEA report, the estimated validity range for the values in Table 2.5. was an annual temperature of 6–10 °C (EEA, 2023), which is lower than the Mediterranean climates in Po Valley and France. In France, given the variability of climatic conditions across such a large scale, and the strong role that climate can play in SOC accumulation, it may have improved the thresholds if they had been stratified by climatic regions as done by Chen et al. (2019). Of course, the thresholds for silt soils may not have been inaccurate, but instead correctly identified that silt soils in Italy and France were more prone to degradation than other soil textures. These different interpretations highlight the importance of using context-appropriate fixed targets and thresholds. However, they are also a good example of how the fixed approach can be used to quickly identify potentially problematic areas, which can then be targeted for further, smaller-scale evaluation.

While the fixed thresholds in Italy may have been too high, particularly for silt soils, it is also likely that the reference targets were too low. This paper used agricultural grasslands as a reference, since grasslands accumulate carbon over time and are characterized by higher SOC than cropland (Fantappiè et al., 2010; Martin et al., 2011; Poeplau and Don, 2013; Taghizadeh-Toosi et al., 2014). The results from France were consistent with that expectation; using the fixed and reference approaches, the targets and thresholds in France consistently identified a higher proportion of at-risk cropland than grassland, while targets and thresholds in the distribution approach were left-skewed in cropland as compared to grassland (Table 3). In both Italy and Denmark, the differences between grassland and cropland were less clear. Italy had a higher proportion of cropland than grassland identified as at-risk using the fixed approach and reference threshold, but not with the reference target. Denmark had very similar proportions of at-risk soils in both land uses using the fixed and reference approaches. This suggests that soils from grasslands in Italy and Denmark may have been degraded, and highlights two important considerations for using the reference approach: the *availability* and *suitability* of a reference situation. In Italy, applying the reference approach was problematic, as only 0.15% of the land area was under permanent grassland, which resulted in the reference values being based on 63 sites (before stratification for soil type), and some STUs where no reference could be calculated. Where grasslands were present, the small number available to act as a reference may have led to a few degraded areas having a large effect on the targets and thresholds produced. While both Italy and France used permanent grasslands as their reference situation, managed grasslands in Denmark are rarely permanent, which complicated the distinction between grassland and cropland from a methodological point of view (*see 2.2.1*). Instead, reference grasslands were defined as areas that had been under grassland for more than five years between 2011 and 2021. Given the indications of degradation within the Danish reference soils, this demonstrates well the importance of choosing an appropriate reference when using the reference approach.

Using the distribution approach to compare cropland and grassland, the 87.5th percentile of the cropland distribution was left-skewed compared to grassland in all three locations. Assuming that no reference was available to see that left-skewedness, this highlights the risk of producing a biased target or threshold, which is an inherent weakness of using the distribution approach on managed soils. Management should also be considered when defining strata, as shown in the results from Denmark. While sandy soils generally have lower SOC targets and thresholds than loam/clay soils (EEA, 2023), the distribution targets in Denmark were similar for both textures in grassland and were actually higher in sand as compared to loam/clay for cropland. Considered just from a soil-type perspective that is surprising, but it may reflect the management practices in Middle Jutland. Sandy soils in the region tend to be in grass-arable rotations, while loamy soils are used for intensive arable farming (*see 2.2.1*), raising the question whether the distribution is in fact reflecting soil type or an interaction of soil and management type, confounding the definition of that strata. Questions of how best to stratify were also reflected by the climate effect in France, where the threshold using the distribution approach identified a more concentrated area of croplands in the south as being at-risk than those in the north. As mentioned above, this would have appeared differently had the distributions also been stratified by climatic region, but the very clear pattern was interesting to note. In contrast, the land areas identified using the distribution method in Italy were largely uninformative. Using the 12.5th/87.5th percentiles in combination with STUs partly located outside the Po Valley was methodologically ineffective, and re-emphasizes that percentiles were chosen arbitrarily and can be adjusted. In the case of Po Valley, a soil health assessment would need to adjust those percentiles to fit the situation. This ability to adjust percentiles or to aggregate/stratify, depending on the question of interest, is one strength of the distribution approach. In a context where underlying factors are not already known, the aggregated assessment can provide valuable data-driven evidence of land use or agricultural practice effects. Stratifying data highlights non-typical areas amongst largely similar soils, which can then be further examined for potentially problematic management practices. However, a critical requirement for the distribution approach is the availability of sufficient, high-quality, covariate data to stratify down to the level of interest. Adequate data is especially important for indicators that may be part of a skewed distribution. Note that sufficient data is, of course, also necessary for the quantification of a reference situation or the development of a fixed value. Therefore, data collection through new monitoring programs and, where possible, soil legacy data (Arrouays et al., 2017; Campbell et al., 2017), will be key to successfully carrying out soil health assessments.

4.2. Potential framework for setting targets and thresholds

At all of the locations (Figs. 1–3; Table 3), the three approaches were able to provide quantitative targets and thresholds that identified potentially at-risk soils for SOC. There was consistency between the values/regions identified by the different approaches, but also some notable differences, highlighting the strengths/weaknesses of each approach (*see 4.1*). Selecting the best approach for assigning targets and thresholds in a given soil health assessment will be a context-specific decision. As an example, target values based on fixed or reference approaches in our case study were lower than those developed using the distribution method. Some exploration of potential methodological issues was explored already, but the purpose of assigning targets is also important to consider. The targets provided in EEA (2023) aim to identify the point at which trade-offs may exist between SOC accumulation and the potential for nitrate loss. In contrast, the distribution targets are much higher, as they simply reflect the highest possible accumulation of SOC that was observed within each strata. Therefore, the decision as to the most appropriate approach will require scientific input to assess the targets and thresholds based on a knowledge of soil properties and functions, as well as stakeholder input to clarify the purpose and needs of the assessment. To facilitate discussions between data/science and policy/stakeholders, a framework is proposed (Fig. 4) that helps to choose the most appropriate approach and follow-up actions for a soil health assessment. While SOC was the example indicator in this paper, the framework can theoretically be used for any single indicator or even multiple indicators such as soil compaction, concentration of different elements, biological diversity and activity or other indicators related to soil health. As data availability will differ between soil indicators and between users (i.e. Member States), the framework can lead to a single soil health assessment (i.e. multiple indicators as part of a single assessment) using multiple target or threshold approaches, and will certainly lead to different users using different approaches. The framework is a decision tree flowchart, in which context plays a key role. While the framework cannot address all the potential influences that context (i.e. ecosystem, stakeholder needs, soil threats) will have on decision-making, it emphasizes the use of more critical/objective approaches where appropriate, by highlighting the confidence associated with those as compared to more subjective approaches, but with the caveat that context may determine that the more objective approaches are unsuitable.

The framework starts with the simplest approach (research-based, fixed targets or thresholds), if sufficient knowledge for a *robust, fit for purpose* value is available.

The fixed approach was not identified as feasible by most webinar participants (Table 2), likely reflecting a recognition of insufficient knowledge (Table 1) and therefore a lack of trust in the use of published targets and thresholds for all contexts. Nevertheless, if an appropriate threshold/target is available, which provides a proven link between the indicator (data) and an outcome of interest (e.g. soil functions, plants, ecosystem health; *see definition of 'fixed' in 1.2*), this should be an ideal approach.

The reference approach appears next in the framework, if context determines that the fixed approach is not suitable. This was the most popular approach identified in the polls. The popularity of the reference approach was likely a combination of simplicity and objectivity (Table 1); those aspects, combined with the lower risk of a *relevant* reference being influenced by degraded soils, are why it is presented before the more subjective distribution approach.

The distribution approach comes third in the framework, when a reference situation is not possible. The use of the distribution approach will often be limited by the availability of data.

Relative change is the forth approach. It was identified in the polls as being the most feasible for widespread use, likely due to the lack of extensive data requirements and the context-specific nature of the data that is used (Table 1).

A final, non-evaluative approach is also included in the framework, when data availability is lacking to identify any target or threshold or there is uncertainty regarding the direction of desired change. In that case, an option can be to simply start with collecting data through monitoring until data requirements are met for one of the four approaches.

Following the selection of a target/threshold approach, the framework proposes the assessment of soil indicator data using percentiles, to normalize across multiple indicators and indicate how far soil data is from the target/threshold. The situation is relatively simple in the case of threshold values; action is needed if the threshold is crossed. For example, the 2023 EU Directive on Soil Monitoring and Resilience (Commission, 2023) provided some specific thresholds for certain soil indicators, and suggested that all of these should be met to define a soil as healthy. Nevertheless, how far a soil is from the threshold may be used as a tool to prioritize the urgency of management changes, depending on the average soil health within the region of interest and/or the level of confidence associated with the threshold. For target values,

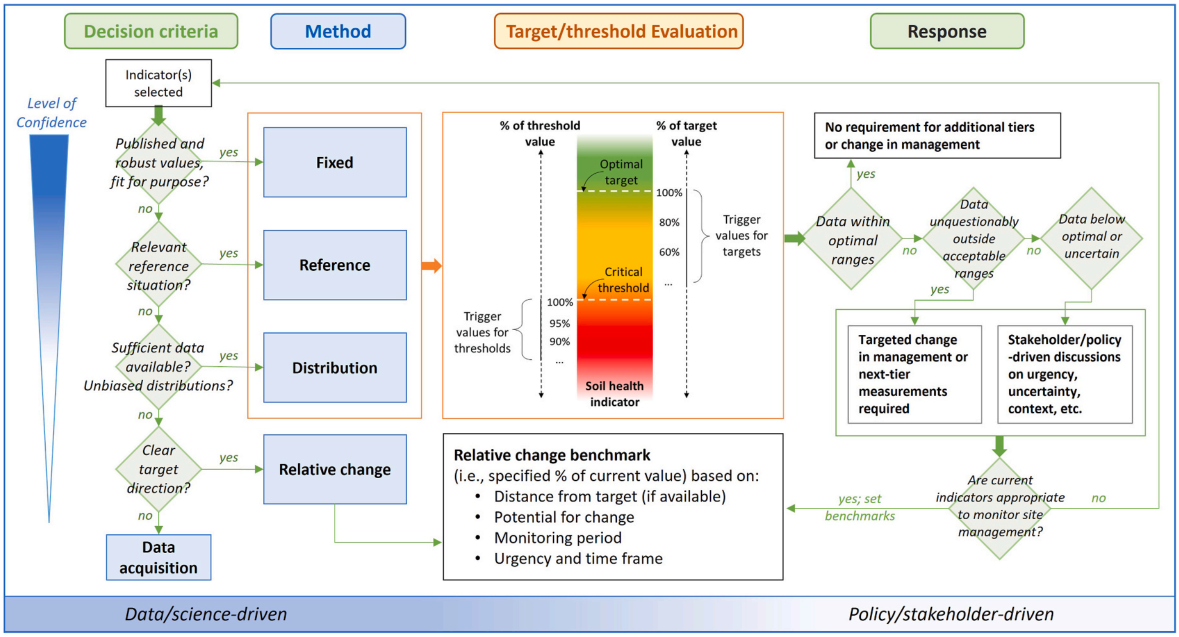

Fig. 4. A framework for the selection and use of targets and thresholds for soil health indicators. The decision tree flowchart first supports the selection of an approach to set targets or thresholds, followed by a method to normalize across different indicators through 'trigger values,' percentiles that indicate how far soil data is from the target or threshold. Based on trigger values, the decision tree flowchart supports responses in management or further data collection.

considering that gap may be even more important. How far should soil indicator data be from an 'optimal' target in order for measures to be implemented? (e.g. less than 70% of the target value?) This addresses the question: "*How good is good enough?*" and would be decided by governance authorities and stakeholders, rather than science. For targets, these 'trigger values' (values defined by stakeholders as being the point at which specific measures will be implemented) should ideally be harmonized between Member States. For thresholds, the choice whether to use trigger values at all, will be a region-specific decision, as described above. While this framework is relevant to any assessment, at any spatial scale, it is particularly well-suited to being integrated into tiered indicator assessments, providing the necessary link to logically trigger additional tiers. If available data suggest that the current indicator(s) are sufficient to assess soil health, management changes may be implemented, and a site may be monitored. Alternately, if current indicators are considered insufficient to inform management decisions, a next tier of indicators may be implemented in the potentially at-risk areas (by returning to the beginning of the framework flowchart) to acquire additional information.

The relative change approach has a central place in the framework, as it can be chosen as the central target/threshold approach, or can be linked into one of the other approaches, as the last step of the framework. The final step of the framework assumes that monitoring soil health improvement will take place using relative-change benchmarks. Setting fixed-term benchmarks will ensure that soil health improvements are context-specific, accounting for the many differences that might affect soil processes and thus how quickly soil indicators will change. Smaller relative changes might be expected from land managers who have done well in the past (see Table 1), and are not as far from an optimal target, as compared to those just starting to implement sustainable management practices. In the case of SOC, slower change may be expected in warm climates, such as the Mediterranean, where SOC decomposes more quickly, as compared to colder climates, where SOC can more easily build up.

4.3. *Conclusion - soil monitoring to support soil health*

Soil monitoring is an essential parallel activity to soil health assessment using the target/threshold framework. First, it is required for the acquisition of background data – a crucial element in using the above framework. If the desired target and threshold approach is known, sampling strategies can be developed to provide the best possible outcomes for that approach. For example, targeting an adequate number and quality of reference areas or sufficient number and quality of samples within desired distribution strata, would address several of the issues observed in our case study. Second, monitoring is a requisite component of maintaining and improving soil health, by understanding trends over time. The establishment of robust soil monitoring systems to determine both the current state and trends of soil health was among the four urgent actions proposed by the UN ITPS to tackle and reverse soil degradation (FAO and ITPS, 2015). Soil monitoring is also one of the specific actions included in the EU Soil Strategy for 2030 (Panagos et al., 2022) and required as part of the 2023 EU Directive on Soil Monitoring and Resilience (Commission, 2023).

Monitoring and assessing soil indicator data using targets and thresholds supports the overall long-term sustainability of agricultural systems and associated ecosystems. At the EU scale, a future approach may be to develop a model by gathering data from national datasets (Cornu et al., 2023) or European datasets (Orgiazzi et al., 2018) in order to cover all climates, soil types and the complete range of the selected indicators as done in the USA (Nunes et al. 2021, 2024). For the present, our framework capitalizes on the strengths of four target and threshold approaches, to provide a flexible yet harmonized system for setting targets and thresholds and using them to trigger follow-up actions that promote soil health. The framework is ambitious, asking users and stakeholders to accept a level of complexity within soil health assessments that allows context to be included. There is no best approach; in any particular assessment -be it at national or smaller, regional scales-, the most appropriate approach will depend on the type and quality of available data, and the purpose of soil health assessment. Yet through identifying targets and thresholds, and monitoring soil data against these targets and thresholds over time, it will be possible to identify trends and assess the impacts of land use changes, management practices and even public policies. This can then guide the development and implementation of new or improved policies and practices that promote and protect soil health.

CRediT authorship contribution statement

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Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123141.

Data availability

No new data was collected for this manuscript. Data sources and citations are provided in the materials and methods.

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