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Soil indicators for sustainable development: A transdisciplinary approach for indicator development using expert stakeholders

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ABSTRACT

Sustainable management of soils is needed to accomplish many of the United Nations' Sustainable Development Goals, but it can be problematic in practice as soils are complex and to manage them sustainably requires the co-operation of multiple stakeholders on various level of society. We present the outcome of a transdisciplinary approach towards indicator development, where we created a set of soil indicators for sustainable development with stakeholder group participation from scientists, policy-makers and soil practitioners. The groups evaluated 49 indicators, through a Delphi survey technique, and selected a set of 30 indicators. Of these 14 were common to all stakeholder groups and represented a final set of core soil indicators for sustainable development. The Delphi survey did suffer from high attrition rate and low response rate, especially among the policy makers, which limits somewhat its findings. Nevertheless, the survey illustrated the usefulness of relevant stakeholder involvement in an indicator development process and the role of survey based instruments in aiding the selection of common indicators, whilst showing the different views of stakeholders groups. Given that the stakeholder groups have to consider a multitude of variables and impacts on soil and may have different focus and management goals in mind, a process such as this can serve as a starting point for discussion between stakeholder groups on various levels of governance about how to manage soil sustainably and help to fulfil the UN's Sustainable Development Goals.

1. Introduction

Soils supply us with food and clean water, they recycle nutrients, decompose contaminants, control water fluctuations, sequester and store significant amount of carbon and provide habitats for the largest number of species of any ecosystems on Earth (Science, 2004; Brevik et al., 2016). Owing to the multiple roles soils have in Earth's ecosystems, humans use them extensively and are thus exerting pressures that have resulted in their degradation (European Commission, 2002; Keesstra et al., 2016). In 2008 there were approximately 1.38 billion hectares of arable land worldwide (FAO, 2010) and up to 5 million hectares are lost every year because of degradation. Soil degradation impacts negatively on the multiple functions of soils (Table 1) and in turn affects more than 1.5 billion people in over 110 countries; 90% of which live in low-income countries (Nellemann, 2009).

In the European Commission's Towards a Thematic Strategy for Soils (European Commission, 2002, 2006) eight main threats to soils are listed (Table 2), illustrating that human activities such as agriculture and forestry practices, industrial activities, road building and soil sealing are major causes of degradation (Turbe' et al., 2010).

With a growing world population, the need for food, clean water and biofuels is on the rise. The demand for food and water is expected to increase by 50% and 30% respectively by the year 2030 (Godfray et al., 2010). Soil degradation presents a serious threat to fulfilling this likely increased demand (Bindraban et al., 2012), and as a result the protection and sustainable management of the soil resource becomes even more important.

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Table 1
Soil functions in Towards a Thematic Strategy for Soils (European Commission, 2002, 2006).

Soil Function Number	Soil functions (SF)
SF1	Food and other biomass production
SF2	Storing, filtering and transformation
SF3	Habitat and gene pool
SF4	Physical and cultural environment for mankind
SF5	Source of raw materials
SF6	Acting as a carbon pool
SF7	Archive of geological and archaeological heritage

Table 2
Soil threats according to the Towards a thematic strategy for soils (European Commission, 2002, 2006).

Soil Threat Number	Soil threats (ST)
ST1	Erosion
ST2	Decline in organic matter
ST3	Soil contamination
ST4	Soil sealing
ST5	Soil compaction
ST6	Decline in soil biodiversity
ST7	Salinisation
ST8	Floods and landslides

1.1. The sustainable development concept

The concept of sustainable development became known in 1987 with the Brundtland Commission's report, *Our Common Future,* and has since then been central to decision-making worldwide (Environment and Development, 1987; MEA, 2005). The 'Brundtland Report' defined sustainable development as development that "*meets the needs of the present without compromising the ability of future generations to meet their own needs*". It centres on the notion of equity, both intra- and intergenerational, and the importance of keeping humanity and its ecological impact within planetary boundaries (UNDESA, 2002; Rockstrom et al., 2009; Steffen et al., 2015).

1.2. Sustainability assessment and indicators

The need for the development of sustainability indicators is clearly set out in Agenda 21 from the Rio UN Summit in 1992 and was taken up by the UN Commission for Sustainable Development (CSD) (Pinfield, 1996). In addition, academics have called for the use of indicators as a means of measuring steps towards sustainability (Bell and Morse, 2008; Easdale, 2016). An indicator demonstrates in what direction something or someone is heading (Ness et al., 2007). By visualizing phenomena and highlighting trends, indicators simplify, quantify, analyse and communicate otherwise complex and complicated information (Warhurt, 2002), and as such they are meant to make complex realities more transparent (Jesinghaus, 1999). Indicators are important tools of sustainability assessment. Sustainability assessment is an iterative, continuing, collaborative process that is an important tool to aid in the shift towards sustainability, helping decision-makers consider the actions that should or should not be taken (UNDESA, 2007). Indicators and assessment tools are therefore essential to reach the various targets and goals relating to sustainable development.

1.3. Sustainable development goals

The United Nations' *Transforming our World: the 2030 Agenda for Sustainable Development* lists 17 Sustainable Development Goals and 169 targets that will stimulate action in critical areas for humanity and the planet until 2030 (United Nations, 2015). Sustainable management of soils has direct relevance for at least half of them and might also be relevant for other goals but in an indirect manner (see Table 1 in Supplementary material). Bouma (2014) and Keesstra et al. (2016) have emphasised the important role of soils in obtaining these goals. It is safe to assume that indicators are needed to report on how sustainably soils are managed in pursuit of the Sustainable Development Goals.

1.4. Soil indicators

Until now indicators for sustainable soil management have mostly been developed within the nature dimension of sustainable development, focusing on the physical, chemical or biological aspects of soils. What has been lacking are the other two dimensions: the social and well-being, and the economic. A plethora of soil indicators for different soil properties, qualities and functions exists in the nature dimension: Arshad and Martin (2002) proposed a minimum data set for soil quality, Marinari et al. (2006) and Fließbach et al. (2007) compared conventional and organic agriculture by using soil properties, and Roldán et al. (2007) used a biological properties of soil approach to compare till and no-till management systems. Rüdisser et al. (2015) proposed linking soil quality indicators with the occurrence of certain soil organism groups and Ritz et al. (2009) looked at national soil monitoring focusing on biological indicators. Muscolo et al. (2015) proposed using biochemical indicators looking at changes in soil organic matter as an early warning system in soil ecosystems. Huber et al. (2008) linked soil indicators directly to soil threats and Thomsen et al. (2012) used soil indicators as chemical stressors in soil systems. These are just a few examples of soil indicators from the literature but as stated before, there is predominance of nature based indicators in the soil sets or frameworks and there is a need to combine indicators from the nature dimension of soil, like soil quality with non-soil biotic, abiotic and socio-economic indicators (Herrick, 2000).

This is the first attempt that we know of that builds a set of soil indicators covering all of the three overarching dimensions of soil sustainable development, using a transdisciplinary approach with active stakeholder participation. In this paper we describe the second stage of developing soil indicators for sustainable development (SIFSD) using a survey based technique involving expert stakeholder involvement.

2. Methods

The complete SIFSD development process is illustrated in Fig. 1. The pre-development aspects, as completed by Jónsdóttir (2011), are indicated in steps 1–5 and that process is not covered in this paper.[1] The pre-development work resulted in 44 theme-based indicators that were used as potential indicators for a Delphi survey that took place in Iceland. Steps 6–8 relate to the Delphi survey outcomes and are the main focus of this paper. Steps 9–10 are only implemented when the indicators are applied to a specific study location and are therefore beyond the scope of this paper.

2.1. The Delphi survey technique

The Delphi survey technique is a vehicle for stakeholder engagement. The technique has been used to address sustainable development issues in many diverse sectors, including mining (Azapagic, 2004), forestry (Sharma and Henriques, 2005), transportation (Mihyeon Jeon and Amekudzi, 2005), environmental

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[1] Information on the pre-development work can be found at: http://skemman.is/stream/get/1946/8865/24238/1/jonsdottir_msc_2011.pdf

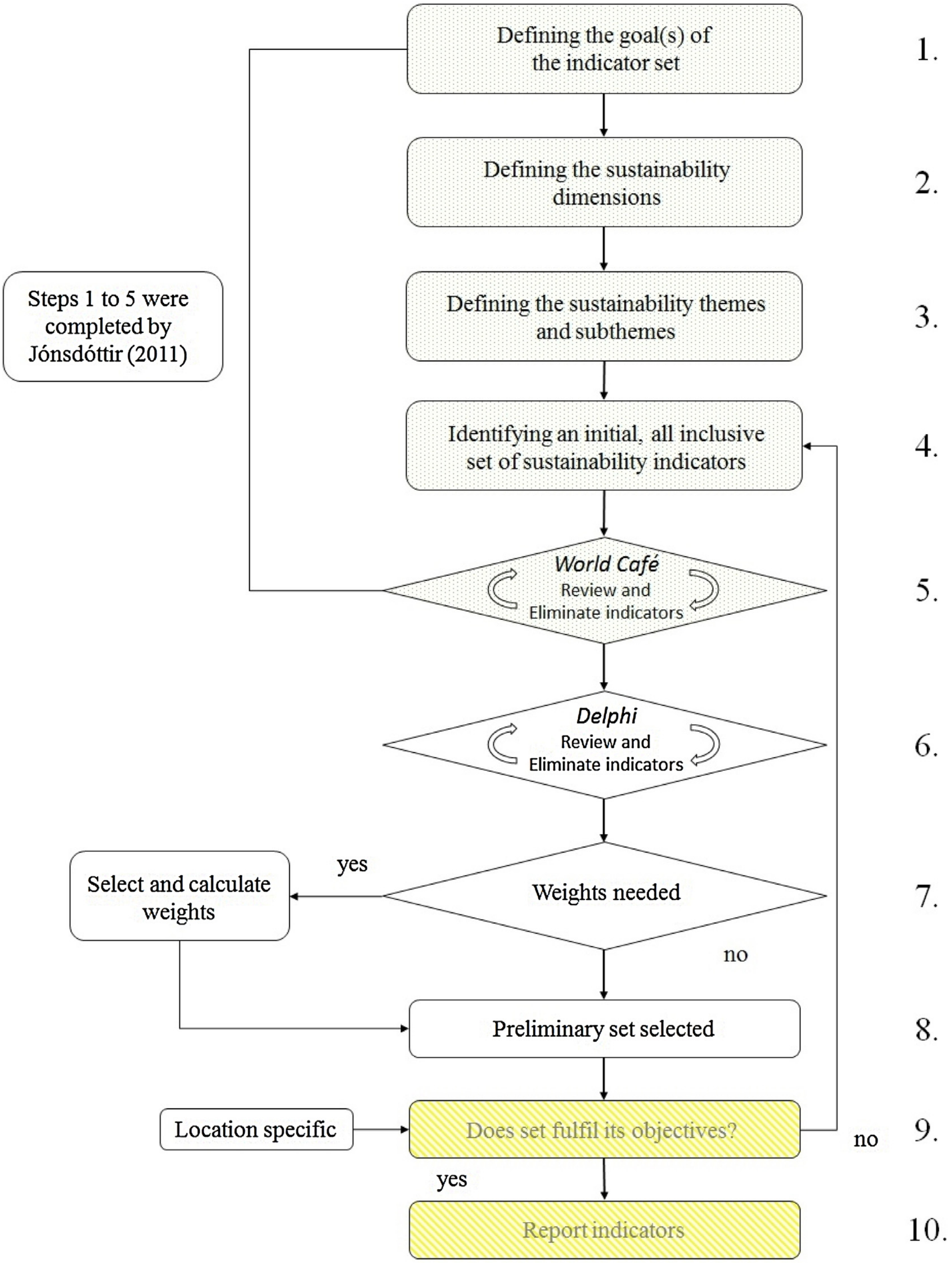

Fig. 1. The SIFSD development process.

management (Bailey et al., 2012) and energy development (Shortall et al., 2015). It is an established survey method for seeking unbiased opinions and consensus on a complex issue, and involves sequential questionnaires answered anonymously by a group of experts. This approach has been used as a consensus-building instrument in fields where opinion is needed from a selected audience with varied views, such as in program planning and policy determination (Gupta et al., 2013; Shortall et al., 2015). The Delphi survey technique has several advantages, including:

- Enables participation of a wide range of individuals with diverse backgrounds;
- Enables participation of individuals located in various regions;
- Provides a more cost effective approach than having on-location workshops;
- Ensures anonymity and thereby reduces the probability of personal conflicts affecting group dynamics; and
- Minimizes bandwagon effects as participants cannot see each other's voting.

Conversely, disadvantages may include a high time commitment; potential hasty decisions by participants as they must vote on each indicator; the risk of a lack of accountability for opinions through anonymity; or the potential for low response rates.

The Delphi technique consists of a structured written survey that is sent to participants, seeking both evaluations (scores) and comments related to specific indicators (Gupta et al., 2013; Shortall et al., 2015). During the first rounds new indicators also can be suggested by the survey participants. During each round of a Delphi survey, the participants give each indicator a score on a scale from 1 – 5, reflecting how relevant it is with 1.00 being Irrelevant, 2.00 Somewhat irrelevant, 3.00 Neither relevant nor irrelevant, 4.00 Somewhat relevant and 5.00 being Extremely relevant. The participants can also give an optional comment in response to each indicator. After each round, the indicator's scores and comments are incorporated into the next round of the survey by facilitators if their scores are high enough and if consensus is on their relevance as reflected by the standard deviation of the scores received. In general, indicators that receive a mean score below 3.00 and with a low consensus are discarded after each round. This process is repeated a few times, until a broad consensus has been reached among the participants for the suggested indicators (Shortall et al., 2015). After the final round, if the mean score minus the standard deviation is less than 3.00, the indicator is rejected. The indicators can then be further reviewed to identify those common to all stakeholder groups and the remainder, which are stakeholder group specific. One drawback of the method is that during the survey process, the mean score, the standard deviation and comments from the participants are all taken into consideration by the facilitators when deciding whether an indicator passes to the next round of the survey. This involves subjective value judgement by the facilitators in some cases.

In this study the Delphi survey was used to engage stakeholder groups and to help to identify i) a set of core soil indicators that all stakeholder groups agree on are important, and ii) a set of satellite indicators that are stakeholder group specific.

2.2. Method implementation

The Delphi survey took place in September/October 2014 in Iceland and ran for three rounds, each taking a week. The survey was distributed via the online survey management system Survey Monkey (surveymonkey.com). Three stakeholder groups participated: scientists (in Iceland and in the SoilTrEC project), soil practitioners (in Iceland), and policymakers (in Iceland). A stakeholder mapping exercise was carried out at the start of the research, with the intention of identifying individuals and organisations that might have an interest in the indicators, or considerable knowledge thereof. Stakeholders were selected based on different characteristics, as recommended in the Australian government stakeholder engagement practitioner handbook (Australian Government, 2008) namely: 1) Responsibility – Stakeholders to whom soil sustainability indicators have a responsibility, such as the local community, the general public, community representatives, environmental organisations and NGOs, local businesses and future generations 2) Influence – Stakeholders with influence or decision-making power when it comes to soil sustainability indicators, such as different levels of government 3) Proximity – Stakeholders that had participated in the first stages of the project, and that have most interaction with soil sustainability, such as researchers, different stages of the government and farmers of various kind 4) Dependency – Stakeholders who are directly or indirectly dependent on soil sustainability, such as farmers of various kind, researchers or food producers 5) Representation – Stakeholders who through regulation, custom or culture can legitimately represent a constituency when it comes to soil sustainability, such as NGOs representing the environment, local authorities, trade unions or local leaders and 6) Policy and strategic intent – Stakeholders that are directly or indirectly address by soil policy or practice, such as farmers, food producers, NGOs or financiers.

Table 3
Stakeholder groups.

	Invited	Round 1	Round two	Round three
Scientists	**27**	15	14	12
- Educational	5			
- SoilTrEC	20			
- Students	2			
Soil practitioners	**41**	17	8	6
- Farmers	13			
- Farmer's association	3			
- NGOs	11			
- Private company	14			
Policy-makers	**20**	11	6	3
- Government institutions	10			
- Policy making/Government	10			
Total	**88**	43	28	21

Initially, 220 people were contacted via email and telephone, prior to being sent a formal invitation to participate via email. All had been identified due to their expertise or work experience within the broad field of soil sciences. Of these, 88 people agreed to participate in the survey. The participants were then invited to an introductory meeting on Wednesday September 3rd, 2014, at the University of Iceland, or to join in that meeting online via Skype. About 20 people attended or joined via Skype.

In the first round an invitation was sent out to 88 people. 43 people finished the first round, 28 the second round and 21 the third (Table 3). Answers from only those who fully completed a round were included in the analysis.

3. Results

3.1. All stakeholder groups

During the three rounds the participants suggested five indicators in addition to the initial 44, and so the total number of indicators evaluated for three rounds was 49 (see Table 2 in Supplementary material). The Final SIFSD set resulted in 30 indicators that were selected by the stakeholder groups. In the nature dimension 17 of 20 indicators were accepted, in the society and well-being dimension 7 of 16 indicators were accepted, and in the economy dimension 6 of 16 were accepted.

3.2. Nature dimension

Of the seventeen indicators selected by the stakeholder groups from the nature dimension, fourteen indicators were included in the soil properties theme, two in the atmosphere theme, and one in the biodiversity theme. The highest scoring indicator in the nature dimension after round three was *Change in total soil organic matter*. The lowest scoring indicator was *Soil iron oxides content compared to reference value* (Table 4).

3.3. Society and well-being dimension

Of the seven indicators selected by the stakeholder groups from the society and well-being dimension, three indicators were in the Institution framework and capacity theme, two in Awareness and

Table 4
Nature indicators scores after each round (R1 – R3), statistics and results for all participants.

	[a]Theme	Sub – Theme	[b]Indicator	[c]R1	R2	R3	[d]Results
NATURE	Atmosphere	Atmosphere	Net carbon sequestration in soil	4.49 (0.55)	4.57 (0.57)	4.48 (0.68)	Accepted
			Extreme weather events	3.60 (1.22)	3.64 (1.03)	3.81 (0.75)	Accepted
			Temperature daytime temperature during the growing season	N/A	3.29 (1.24)	3.48 (0.93)	Rejected
	Biodiversity	Biodiversity	Pedodiversity	3.95 (0.90)	3.82 (0.77)	4.00 (0.89)	Accepted
	Soil Properties	Physical	Aggregate diversity	4.38 (0.79)	4.29 (0.76)	4.25 (0.64)	Accepted
			Bulk density	4.16 (0.75)	4.21 (0.83)	4.24 (0.77)	Accepted
			Change in topsoil depth	4.33 (0.97)	4.37 (0.69)	4.10 (0.89)	Accepted
			Soil sealing	4.17 (1.03)	4.44 (0.70)	4.38 (0.74)	Accepted
			Strata composition and buffer capacity	N/A	4.07 (0.94)	3.76 (1.14)	Rejected
			Soil erosion	N/A	3.96 (1.00)	4.19 (0.93)	Accepted
		Chemical	Change in cation exchange capacity (CEC)	4.14 (0.86)	3.93 (0.73)	3.85 (0.75)	Accepted
			Soil contamination	4.44 (0.96)	4.46 (0.96)	4.38 (1.12)	Accepted
			Change in topsoil pH	4.14 (1.01)	4.36 (0.78)	4.33 (0.73)	Accepted
			Soil iron oxides content compared to reference value	N/A	3.61 (0.69)	3.24 (1.14)	Rejected
		Biological	Change in microbial biomass	4.17 (1.08)	4.39 (0.57)	4.24 (0.94)	Accepted
			Change in and absolute level of net N mineralization	4.16 (1.04)	4.21 (0.79)	4.24 (0.62)	Accepted
			Soil protective cover	4.44 (0.93)	4.50 (0.75)	4.24 (0.77)	Accepted
			Change in total soil organic matter (TSOM)	4.70 (0.56)	4.64 (0.49)	4.48 (0.68)	Accepted
			Change in flora diversity above ground	N/A	4.14 (0.71)	4.30 (0.57)	Accepted
			Change in fauna diversity above ground	N/A	4.04 (0.79)	4.14 (0.73)	Accepted

[a] Themes within one of the overarching dimensions of sustainable development.
[b] Proposed soil indicator for sustainable development.
[c] Rounds one to three with mean score, standard deviation in parenthesis.
[d] Results after round three considering score, standard deviation and comments from participants.

public participation, one in Health, and one in Demographics. The highest scoring indicator in this dimension was *Public awareness of the value of soil*, which also was the highest scoring indicator in the survey after round three. The lowest scoring indicator was *Age diversity in rural areas* (Table 5). Two indicators, *Armed conflicts* and *contaminated Soils*, were moved to the nature dimension after round two after suggestions from many of the participants in the survey.

Table 5
Society and well-being indicators scores after each round (R1 – R3), statistics and results for all participants.

	[a]Theme	Sub - Theme	[b]Indicator	[c]R1	R2	R3	[d]Results
SOCIETY AND WELL-BEING	Institutional framework and capacity	Governance level	Access to information and justice	3.53 (1.32)	3.54 (1.29)	3.33 (0.86)	Rejected
			Government policies	3.85 (1.15)	4.21 (1.26)	4.10 (0.89)	Accepted
			Land tenure security	3.74 (0.82)	3.71 (0.98)	3.62 (1.12)	Rejected
		Science, technology and education	Expenditure on soil related research and development	3.77 (1.31)	4.04 (1.07)	4.10 (1.00)	Accepted
			Literacy	3.21 (1.49)	3.43 (1.20)	3.43 (1.40)	Rejected
			Education on sustainability	3.91 (1.34)	4.18 (1.02)	4.05 (0.92)	Accepted
	Awareness and public participation	Awareness and public participation	Public awareness of the value of soil	4.12 (1.18)	4.43 (0.92)	4.52 (0.68)	Accepted
			Public participation	3.72 (1.32)	3.86 (1.08)	3.95 (0.86)	Accepted
			Public access to nature areas	N/A	3.25 (1.17)	3.52 (0.98)	Rejected
	Health	Health	Human health (healthy life years)	3.37 (1.29)	3.39 (1.50)	3.33 (1.02)	Rejected
			Bioavailability of essential major and trace elements	3.51 (1.28)	4.32 (0.90)	4.00 (1.00)	Accepted
			Suicide rate of farmers	2.53 (1.32)	N/A	N/A	Rejected
	Demographic	Demographic	Age diversity in rural areas	3.19 (1.62)	3.32 (1.12)	3.19 (1.08)	Rejected
			Population growth	3.77 (1.32)	3.96 (1.04)	4.00 (0.77)	Accepted
	Security	Security	Armed conflicts	3.47 (1.42)	3.71 (1.21)	N/A	Moved*
			Contaminated soils	3.70 (1.30)	4.25 (0.89)	N/A	Moved*

[a] Themes within one of the overarching dimensions of sustainable development.
[b] Proposed soil indicator for sustainable development.
[c] Rounds one to three with mean score and standard deviation in parenthesis.
[d] Results after round three considering score, standard deviation and comments from participants. *The indicator was combined with Soil contamination in the nature dimension after recommendations from participants.

3.4. Economy dimension

Of the six indicators selected by the stakeholders in the economy dimension, four indicators were in the theme Industry specific indicators for agriculture and forestry, one in Consumption patterns, and one in economic value of soil ecosystem services. The highest scoring indicator after round three in the economy dimension was *Soil salinity due to irrigation* and the lowest scoring indicator was *Labour intensity*, which was also the lowest scoring indicator overall after round three. Based on suggestions from participants, two indicators were merged with others within the economy dimension: *Economic loss due to loss of soil ecosystem services* was merged with *Economic value of soil ecosystem services* and *Diversity in land management* was merged with *Change in land use diversity* (Table 6).

3.5. Core indicators and satellite sets

Table 7 shows the core indicators (highlighted) that are common to all stakeholder groups, the soil functions that the indicators represent and the threats they address. The core indicators selected by the stakeholder groups cover all the functions and threats, with most of them covering multiple functions and threats (see Table 2 in Supplementary material provided for more information on each indicator). Table 7 also shows the metrics for measuring all the indicators suggested, along with the scale of the measure and frequency. The metric, scale of measurement and the frequency of measurement are based on the outcome of stakeholder inputs both from Jónsdóttir (2011) and from participants in the Delphi survey.

Some of the stakeholder groups included particular indicators that the other groups did not contain, and are referred to here as satellite indicators. The stakeholder group *policy makers* had the most satellite indicators, eight in total. The group had three in the economy dimension, five in the society and well-being dimension, and none in the nature dimension. In the economy dimension two of the three indicators for the policy makers belonged to the consumption patterns theme but different sub-themes. In the society and well-being two of the five indicators belonged to the Institutional framework and capacity theme but different sub-themes. The satellite set for soil practitioners had two indicators: *Extreme weather events* and *Strata composition and buffer capacity,* both belonging to the nature dimension. The satellite set for scientists contained only one indicator: *Expenditure on soil related research and development.*

4. Discussion

Based on extensive stakeholder engagement, the final results consist of a core set of 14 soil indicators that all stakeholder groups deemed important in the context of sustainable development, in addition to satellite sets specific to each stakeholder group. The indicator set is markedly different from the soil indicator sets mentioned in section 1.4 as it covers all the dimension of sustainable development, not solely the nature dimension like the other sets do. The results show that the opinions of the

Table 6
Economy dimension indicators scores after each round (R1 – R3), statistics and results for all participants.

	[a]Theme	Sub - Theme	[b]Indicator	[c]R1	R2	R3	[d]Result
ECONOMY	Economic value of soil ecosystem services	Economic value of soil ecosystem services	Economic value of soil ecosystem services	3.77 (1.17)	3.46 (1.10)	4.00 (0.89)	Accepted
			Economic loss due to loss of soil ecosystem services	3.81 (1.17)	3.32 (1.16)	3.81 (0.87)	Merged[*]
	Consumption patterns	Land use	Change in land use diversity	3.67 (1.25)	3.61 (1.23)	4.00 (0.71)	Accepted
			Local food consumed	N/A	3.37 (1.31)	3.62 (1.07)	Rejected
		Waste	Waste generation intensity	3.35 (1.49)	3.32 (1.36)	3.33 (1.02)	Rejected
			Organic waste composted and returned to soil	3.74 (1.35)	3.75 (1.21)	4.10 (1.14)	Rejected
	Industry specific indicators for agriculture and forestry	Productivity	Yield, given no change in fertilization	4.02 (1.24)	3.85 (1.03)	4.05 (0.59)	Accepted
		Economic viability	Return on equity (ROE)	3.40 (1.31)	2.96 (1.20)	N/A	Rejected
			Debt to asset ratio	2.88 (1.24)	N/A	N/A	Rejected
		Input intensity	Energy returns on investment (EROI)	3.21 (1.35)	3.54 (1.17)	3.43 (0.87)	Rejected
			Fossil energy intensity	2.81 (1.31)	N/A	N/A	Rejected
			Chemical fertilizer use intensity	3.77 (1.34)	3.96 (1.00)	4.19 (1.03)	Accepted
			Pesticide use intensity	4.05 (1.27)	4.18 (1.16)	4.19 (0.81)	Accepted
			Soil salinity due to irrigation	3.95 (1.23)	3.89 (0.96)	4.24 (0.70)	Accepted
			Labour intensity	3.40 (1.29)	3.29 (1.15)	3.00 (1.03)	Rejected
		Industry practices	Diversity in land management	3.95 (1.19)	4.04 (1.07)	N/A	Merged[**]

[a] Themes within one of the overarching dimensions of sustainable development.
[b] Proposed soil indicator for sustainable development.
[c] Rounds one to three with mean score and standard deviation in parenthesis.
[d] Results after round three considering score, standard deviation and comments from participants.
[*] The indicator was merged with Economic value of soil ecosystem services as it is representing the same thing.
[**] The indicator was merged with Change in land use diversity after recommendations from participants.

Table 7
Soil indicators for sustainable development. Core set of soil indicators is highlighted.

Dim.[a]	Theme[b]	Sub-theme[c]	Indicator[d]	Metrics[e]	Link to soil functions (Table 1)[f]	Link to soil threats (Table 2)[g]	Scale[h]	Measurement frequency[i]	SC[j]	SP[k]	PM[l]
NATURE	Atmosphere	Atmosphere	Net carbon sequestration in soil	C equivalent $gC/m^2/yr$.	SF1–SF3, SF6	ST1 – ST6	Plot	Annual, seasonal, monthly	X	X	X
			Extreme weather events	Days/season, quantity/ intensity	SF1 – SF7	ST1 – ST3, ST6 – ST8	Plot	Seasonal		X	
	Biodiversity	Biodiversity	Pedodiversity	Number of soil classes within an area	SF1 – SF7	ST1-ST8	Plot	Annual or less frequently	X	X	X
	Soil Properties	Physical	Aggregate diversity	Mean weight Diameter of various aggregates, and aggregate diversity measured with the Shannon Wiener index	SF1 – SF3, SF6	ST1, ST2, ST5, ST6, ST8	Plot	Annual, seasonal	X	X	X
			Bulk density	g/cm3	SF1 – SF3, SF6	ST1, ST2, ST5	Plot	Annual or less frequently	X	X	X
			Change in topsoil depth	cm	SF1 – SF7	ST1, ST2, ST6, ST8	Plot	Annual or less frequently	X		X
			Soil sealing	% of total land area, excluding land under water and ice	SF1 – SF7	ST4, ST5, ST8	Plot	Annual	X	X	X
			Strata composition and buffer capacity	Absorption and permeation in the strata, and chemical composition. Field capacity. Water retention.	SF1, SF2	ST2, ST4, ST5	Plot	Annual		X	
			Soil erosion	µg/m3 of particulate	SF1 – SF7	ST1, ST2, ST6	Plot, national	Hourly	X	X	X
		Chemical	Change in cation exchange capacity (CEC)	C mole/kg.	SF1 – SF3, SF6	ST2, ST3, ST6, ST7	Plot	Once every 5 years		X	X
			Soil contamination	Concentrations in topsoil	SF1 – SF6	ST2, ST3, ST6	Plot	Annual		X	X
			Change in topsoil pH	pH	SF1 – SF3, SF5 – SF7	ST2, ST3, ST6, ST7	Plot	Several times a year	X	X	X
		Biological	Change in microbial biomass	$C\ (mg\ kg^{-1})$	SF1 – SF4, SF6	ST2, ST3, ST6	Plot	Annual		X	X
			Change in and absolute level of net N mineralization	mg/kg soil	SF1 – SF3, SF6	ST2, ST6	Plot	Annual, seasonal	X	X	X
			Soil protective cover	% per season	SF1 – SF4, SF6	ST1, ST2, ST6	Plot	Annual, seasonal	X		X
			Change in total soil organic matter (TSOM)	%	SF1 – SF4, SF6	ST2, ST6	Plot	Annual	X	X	X
			Change in flora diversity above ground	Shannon's index and Simpson's index	SF1 – SF3, SF6	ST6	Plot	Annual	X	X	X
			Change in fauna diversity above ground	Shannon's index and Simpson's index	SF1 – SF3, SF6	ST3	Plot	Annual	X	X	X
Number of indicators in nature dimension									*13*	*16*	*16*
ECONOMY	Economic value of soil ecosystem services	Economic value of soil ecosystem services	Economic value of soil ecosystem services	€	SF1 – SF7	ST1 – ST8	Plot, national	Annual	X		X
		Land use		% of land cover	SF1 – SF7	ST1 – ST8	Regional		X		X

Table 7 (*Continued*)

Dim.[a]	Theme[b]	Sub-theme[c]	Indicator[d]	Metrics[e]	Link to soil functions (Table 1)[f]	Link to soil threats (Table 2)[g]	Scale[h]	Measurement frequency[i]	SC[j]	SP[k]	PM[l]
	Consumption patterns		Change in land use diversity					Annual, seasonal			
			Local food consumed	The percentage of local food (produced within certain radius from sales point) bought by consumers	SF1, SF4	ST2	Plot	Annual			X
		Waste	Waste generation intensity	ha	SF1 – SF5	ST3, ST4, ST6	Local	Annual			X
			Organic waste composted and returned to soil	%	SF2 – SF6	ST2, ST6	National, larger international regions	Annual		X	X
	Industry specific indicators for agriculture and forestry	Productivity	Yield, given no change in fertilization	Tonnes/ha	SF1, SF2, SF6	ST1 – ST8	Farm	Annual	X	X	X
		Input intensity	Energy returns on investment (EROI)	kcal out/kcal in	SF1, SF5	ST1 – ST8	Farm, local	Annual			X
			Chemical fertilizer use intensity	Kg/ha per yield (kg) by crop type/ha	SF1 – SF3, SF6	ST2, ST3, ST6	Farm, national, larger international regions	Annual	X		X
			Pesticide use intensity	Kg/ha per yield (kg) by type/ha	SF2 – SF4	ST2, ST3, ST6	Farm	Annual	X	X	X
			Soil salinity due to irrigation	g/kg (Na, K, Ca, Mg salts)	SF1 – SF3, SF6	ST1 – ST3, ST6 ST7	Farm	Annual	X		X
Number of indicators in economy dimension									*6*	*3*	*10*
SOCIETY & WELL-BEING	Institutional framework and capacity	Governance level	Access to information and justice	Has the Aarhus Convention on Access to Information, Public participation in Decision-making and Access to Justice in Environmental Matters been ratified or not	SF1 – SF7	ST1 – ST8	National	Annual or less frequent			X
			Government policies	Existence of soil related policies	SF1 – SF7	ST1 – ST8	National	Annual or less frequent	X		X
			Land tenure security	Long term (> 30 years) versus short term (< 30 years)	SF1 – SF7	ST1 – ST8	National	Annual or less frequent			X
		Science, technology and education	Expenditure on soil related research and development	% of overall research expenditure	SF1 – SF7	ST1 – ST8	National	Annual	X		
			Literacy	% population	SF1 – SF7	ST1 – ST8	National	Annual or less frequent			X
			Education on sustainability	%	SF1 – SF7	ST1 – ST8	National	Annual	X		X
	Awareness and public participation	Awareness and public participation	Public awareness of the value of soil	% of population, measured with survey	SF1 – SF7	ST1 – ST8	National	Annual or every five years	X	X	X

		Public participation	% of population, measured with survey	SF1 – SF7	ST1 – ST8	National	Annual			X
		Public access to nature areas	Proximity to cities, amount of public and national parks	SF1 – SF7	ST1 – ST8	National	Seasonal	X		
Health	Health	Human health	Healthy life years	SF1, SF2	ST1, ST2, ST6	National	Annual			X
		Bioavailability of essential major and trace elements	Mg/kg	SF1, SF2	ST1, ST2, ST6	Farm	Annual or less frequent		X	X
Demographic	Demographic	Population growth	%	SF1 – SF7	ST1 – ST8	National	Annual	X		X
Number of indicators in society and well-being dimension								*6*	*2*	*10*
Total number of indicators in each group								**25**	**21**	**36**

[a] Dimensions of sustainable development.
[b] Themes within the selected dimensions of sustainable development.
[c] Sub-theme within one of the themes.
[d] soil indicator for sustainable development.
[e] What is used to measure the indicator.
[f] Soil functions in the Soil Thematic.
[g] Soil threats according to the Soil Thematic.
[h] The measurement scale.
[i] How often measured.
[j] Scientists.
[k] Soil practitioners.
[l] Policy makers.

stakeholder groups somewhat vary (Table 7) is to be expected, as the indicators considered important by one group may not be deemed as important by another as their level of decision-making differs. The most obvious difference occurs between the soil practitioners and policy makers. On the one hand the selection of the soil practitioner's group shows a clear focus on the soil system itself, as 16 of the 21 indicators are placed in the nature dimension, leaving only 6 indicators that are divided between the other two dimensions. The soil practitioner's group also had the lowest number of indicators. The policy makers, on the other hand, had the largest group of indicators, 36 in total, and the most diverse set, including indicators in all three dimensions. The scientist group selected 25 indicators in total, with similar to the soil practitioners most of these located in the nature dimension. When looking at what issues all stakeholder groups deem important it becomes apparent that the indicators that all three groups have in common are mostly linked to the nature dimension, clearly capturing the links to the various functions that the soil performs and especially relating to soil physical and biological properties. This result is in line with other soil sustainability indicator sets that have been designed that largely focus on nature-based indicators (see Section 1.4). Furthermore, the proposed indicators for soil properties within the nature dimension are generally strongly affected by human activities, such as land use, land management, emissions, waste disposal etc. as well as representing key measures of soil quality. A surprise was the selection of *Public awareness of the value of soil* as the highest scoring indicator, which conflicted with our expectation that a nature based indicator would be deemed the most important. But as Brussaard et al. (2007) point out, "the values of soils are largely hidden and are usually less appreciated than those of above-ground assets". This leads to a lack of awareness and then to limited ability to connect the importance of soil protection to broader environmental, social and environmental outcomes (Bennett et al., 2010). The awareness of our stakeholder groups to this fact explains, in our view, the importance of this indicator and why it ranked number one.

In order for indicators to be influential, consensus must exist among actors that the chosen indicators are legitimate, credible and salient. This means that the indicators must not only answer questions that are relevant to each actor, but also provide a scientifically plausible and technically adequate assessment. To be legitimate, the indicators must be developed through a politically and socially acceptable procedure. The Delphi process used in this study lends legitimacy, credibility and saliency to the indicators that were produced. This can be seen by scrutinizing the change in standard deviation between rounds 1 and 3 for all the indicators (Tables 5–7), as this decreased for all indicators apart from five, indicating a development of a consensus in the group of respondents. Although it is difficult to evaluate whether true group learning or social learning occurred as a result of the Delphi, without doing a post-Delphi survey, it can be assumed that participants most likely benefitted from the Delphi process through the unfolding of greater understanding of the issues surrounding the sustainable development of soil. This is reflected through the Delphi process as it provides both quantitative and qualitative information from the stakeholders. The stakeholder input for the Delphi survey was also useful to the authors in designing better soil indicators generally, as the process illuminated problems with the theory behind and definition of certain indicators or reference values.

The main weaknesses of our approach were the high attrition and relatively low response rates in the Delphi survey. For example, participant's number went from 43 down to 21 between round one and three, with a particularly severe impact on the policy makers group that had a particularly high drop-out rate. As this certainly affects our ability to generalize from our survey, this seems not to have biased the final selection of core-indicators, as selections by the policy makers were not the limiting group when selecting the indicators as they chose the largest and most diverse set.

As the indicators have not yet been formally implemented, it is difficult to evaluate their practical suitability. However, many of the indicators are already used, just not in the specific context of soil and sustainable development (see for example: the various agri-environmental indicators in the OECD, Eurostat and FAOSTAT agri-environmental indicator sets where they report on fertilizer, pesticide, land use and soil erosion and others; the Human Development Index indicator on literacy; and World Bank's World Development Indicators where the World Bank reports on research and development expenditure and population growth among other things). To create a generalizable and universally applicable indicator set further studies are needed. It will be necessary to run the same indicator development process in different national and development contexts to evaluate indicator applicability for sustainable development given diverse economic, social and natural environments. This is an important process, as no one indicator set or framework can cover all soil systems and study locations (Van Cauwenbergh et al., 2007). Interesting results may emerge through a comparison of the outcomes from national studies focused on perceptions of the most important aspects of soil to monitor.

There are clear advantages of maintaining a core set of indicators and the stakeholder specific sets (SDSN, 2015) as this caters to soil managers that operate at different scales, decision-makers and the public. As reported in Dahl (2012), the general public and decision makers prefer a limited set of 10–15 indicators of the most relevant trends, but other stakeholder groups prefer a broader set. Selecting stakeholder specific indicators is a delicate matter as Van Cauwenbergh et al. (2007) asserts – selecting too few indicators promulgates the danger of omitting some important aspects, whilst selecting too many complicates data processing, data collection and interpretation. Our final results provide a core indicator set of 14 indicators and then broader satellite sets for specific stakeholder groups, ranging from 21 to 36 indicators (Table 7). We believe that by having both the core and satellite sets, we might be able to thread the narrow path between having too few and too many.

The UN 2030 Sustainable Development Goals cannot be reached with the continuing degradation of soils. Rapidly depleting soil resources will severely limit the options of future generations to fulfil their needs. How we humans safeguard soils for current and future generations is of utmost importance and needed for that are methods and tools to monitor soils systematically and holistically. In this paper we have presented a process for developing soil indicators for sustainable development. Indicators are important tools that can be used to monitor soil resources, and by using an expert-based stakeholder approach where soil managers across various levels of society participate it is more likely to reach a consensus on what constitute the elements of soils that should be monitored. We believe that by using an indicator development process with extensive stakeholder participation and consultation on different levels of soil management gives legitimacy and credibility to the final outcome: the core Soil Indicators for Sustainable Development (SIFSD). Many of the chosen indicators have established methods and are currently used, though some of them have perhaps not been used before in the context of soil. A few, such as *Economic valuation of soil ecosystem services*, have so far lacked established methods for evaluation, but there have been recent developments seeking to address this (see for example: Dominati et al., 2014; Graves et al., 2015; Jónsson and DavíÐsdóttir, 2016). The issue of soil sustainability is fundamental to reach the SDG as "the quality and health of soil determine agricultural sustainability, environmental quality, and as a consequence of both, plant, animal and human health" (Doran and Zeiss, 2000). Koch et al. (2013) call for a soil-centric policy framework "to generate policies that raise awareness of, and reverse, soil degradation and simultaneously recognize co-benefits for sustainable development". We believe that soil indicators for sustainable development might serve as contribution towards that end.

5. Conclusion

We presented a set of soil indicators for sustainable development – developed by using a transdisciplinary approach with extensive stakeholder participation. This type of indicator set can be a useful tool to assist decision-making regarding soil management. It can serve a communication medium or a middle ground, as the core soil indicator set represents something that all stakeholders agree on as being relevant for sustainable development in the context of soil. It is, therefore, a starting point. The use of an indicator set in decision-making, regardless of its suitability is, however, never guaranteed. We assert that the extensive stakeholder participation involved in the soil indicator development process lends credibility to the selected core set and, furthermore, will increase the likelihood of its future adoption.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.08.009.

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