Methods for deriving selected soil quality indicators

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Abbreviations

CGIAR	Consultative Group on International Agricultural Research
EC	European Commission
FAO	Food and Agriculture Organisation of the United Nations
LANDMARK	Land Management Assessment Research Knowledge base
LUCAS	Land Use and Coverage Area Frame Survey (EC)
IITA	International Institute of Tropical Agriculture
KALRO	Kenya Agricultural and Livestock Research Organization
SIS	Soil Information System
WUR	Wageningen University & Research
WP	Work Package

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1. Introduction

The need for sustainable intensification in Africa

The green revolution has allowed food production to sharply increase worldwide from the middle of the 20th century, with a more than 3-fold increase in the past 50 years (www.fao.org/faostat). At the same time, agriculture has become the single largest driver of environmental change, strongly contributing to climate change, fresh water and marine ecosystem eutrophication, species extinction and biodiversity loss, soil erosion and nutrient depletion, and ecosystem over-simplification leading to the loss of numerous ecosystem services (Fuchs et al., 2020; Tilman et al., 2001). The large-scale, capital-intensive type of agriculture that arose from the green revolution has turned out to be particularly poorly suited to the African context (Leakey, 2017). Smallholder farmers' income strongly limits their access to the technological package with pesticides, mineral fertilisers, improved seed varieties and mechanisation (Leakey, 2017). As a result, increasing agricultural production in Africa is obtained through continuous expansion and shortening of fallow periods. This has resulted in widespread land degradation (FAO and ITPS, 2015), but does not allow production to match the growing population and demand for agricultural products (Silva et al., 2021). Indeed, production in Africa per capita has stagnated at the continental scale since the 1960's (but disparities between regions exist with a 10-30% increase in west and central Africa and more than 20% decrease in south and east Africa). In contrast, it sharply increased in the rest of the world, particularly Asia and South-America (Pretty et al., 2011). The result for Africa can be referred to as "the cycle of land degradation and social deprivation" (Leakey, 2017), a downward spiral where severe land and soil degradation, low agricultural productivity, poverty, poor education, lack of infrastructure and social exclusion are inextricably interconnected. Therefore, the link between food production and food security is absolutely clear for smallholder African farmers, with an estimated 7% reduction in poverty for every 10% increase in yield (Pretty et al., 2011).

It is now widely recognised that agricultural systems (agro-ecosystems) are multi-functional and support a range of ecosystem services, including provisioning (e.g. food, fuel, fibre production), regulating (e.g. water purification), supporting (e.g. nutrient cycling) and cultural services (e.g. recreation, aesthetic value) as well as climate regulation by carbon sequestration (Hassan et al., 2005). The loss of some of these ecosystem services, as a consequence of agricultural use without consideration for sustainability, jeopardises environmental stability, as well as the productive capacity of soils in agroecosystems (Loos et al., 2014). Everywhere, but particularly in Africa, socio-

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economic wellbeing is inextricably linked with agricultural production which directly depends, in the long run, on our ability to maintain these agro-ecosystems services (whose degradation can result in environmental degradation and associated poverty). Therefore, past and continued degradation of agro-ecosystems, together with population growth, pose food insecurity as an escalating concern and place a double injunction on agriculture: (i) produce enough food and income for a growing population and (ii) minimise its negative environmental footprint and preserve the services it provides, including the sustained ability to produce food. It is clear that these twin challenges call for a shift in paradigm to place sustainability as the key strategy for agricultural development (Rockström et al., 2017). To promote such a strategy, the term *sustainable intensification* has already been widely adopted by international research and policy organisations such as the FAO (Food and Agriculture Organisation of the United Nations) and the CGIAR (Consultative Group on International Agricultural Research) (Tittonell, 2014) and comes forward to Sustainable Development Goal (SDG) 2.4. The term sustainable intensification has been used widely and was often diverted from its original meaning (Loos et al., 2014), but it can, nonetheless, be a guiding principle for agriculture to promote food security and environmental stewardship provided that it remains true to its early definition and intent (Loos et al., 2014). The general principles are reiterated here, based on Pretty (2018). Sustainable intensification aims to improve overall system performance without net environmental cost, while avoiding the cultivation, or other exploitative agricultural uses, of more land and the loss of natural habitats. It emphasises the importance of local knowledge and builds on it to develop locally suited adaptative methods, acknowledging that no system is expected to succeed forever if only exploitative. The concept emphasises a wide set of environmental and socially progressive outcomes rather than means and does not predetermine any type of technology, production type or design component. It is in essence a "Systems Agronomy" approach as defined by (Giller et al., 2015) considering the various aspects of farming systems: "an empirically grounded, adaptive approach that focuses not only on production and environment, but also calls attention to social acceptability and economic viability".

Soils and Sustainable intensification

Soils are recognised as the second most essential resource to human life on the planet, after water (van Leeuwen et al., 2017). Regrettably, they also are the first victim of inadequate agricultural management practices largely due to overexploitation. Continuous erosion, organic matter loss and nutrient depletion are at the centre of the spiralling decay in the productive capacity of African agro-ecosystems (Bekunda et al., 2010). Careful attention to soil fertility has long been recognised as a pre-requisite towards agricultural and sustainable intensification (Bekunda 2010), but a debate about how to improve soil fertility to maintain soil productive capacity on the long-term, while realising productivity on the immediate term, has been ongoing for decades and boils down to the question if external nutrient inputs are conducive or inconducive (or required) for attaining an overall sufficient and sustainable production level. The debate is now complexified by the recognition that beyond soil fertility, soil in its whole is key to supporting a wide range ecosystem services, with recent literature describing five 'soil based ecosystem services', or functions: (1) support for primary production, (2) water purification and regulation, (3) carbon sequestration and climate regulation, (4) soil biodiversity and habitat provisioning and (5) recycling of nutrients (Schulte et al., 2014; van Leeuwen et al., 2017). Only empirical evidence and greater scientific knowledge will resolve the debate and inform soil management allowing us to meet the twin challenges of food security (function 1) and environmental sustainability (functions 2-5) (Schulte et al., 2014) as mentioned in SDG 2.4.

Soils4Africa project and the selection of Soil Quality indicators

Soils4Africa sits at the intersection of two observations: (i) Africa needs sustainable intensification and (ii) soils are key to sustainable intensification and direct beneficiary next to agricultural productivity. Therefore, Soils4Africa aims to collect soil data and develop an open-access Soil Information System (SIS) for Africa to support decision-making towards sustainable agricultural intensification in Africa and facilitate future monitoring and evaluation.

The project consists of seven interlinked work packages (WP). This report is the first deliverable of WP3 and describes the outcome of its first activity (activity 3.1): "*selection of indicators and development of methods for quantification*". The selection of Soil Quality indicators is informed by the inventory of use requirements defined in WP2. Particularly, it builds on deliverable 2.1 (D2.1) which describes a set of use case categories representative of the needs of a variety of African stakeholders involved in the use of soil information and SIS for governance, knowledge generation and operational use. The set of selected Soil Quality indicators will define which parameters need to be measured and therefore inform the field sampling protocols and guidelines for fieldwork, the protocols for laboratory analyses and the development of the functional design of the SIS, which is the global aim of WP3.

As specified in the proposal, a minimum set of soil parameters (particle size distribution, pH, organic carbon content, carbonate content, total nitrogen content, extractable (available) phosphorus content and extractable (exchangeable) potassium content) is considered as the minimum information needed to support the quantification of soil quality from an agricultural perspective. These parameters will be assessed using spectral techniques for all soil samples collected at the 20,000 locations (from the topsoil and, for selected sites, also from the mid and subsoil) across the five geographical regions described in the proposal of which a defined portion will also be analysed by wet chemistry. Out of those 20,000 sites, 250 will be selected as reference sites that are considered representative sites for the continent. Further observations will be made at these 250 sites for a better understanding and interpretation of Soil Quality, not just from an agricultural perspective, but also considering the environmental functions supported by soil.

The present report describes the process to identify the parameters necessary for the quantification of indicators that evaluate the impact of agricultural management practices on the agricultural soils of Africa and assess their sustainability. The selection process has considered the use requirements for soil information as described above from identified use case categories and existing Soil Information Systems in Europe such as the LUCAS Topsoil survey (Orgiazzi et al., 2018). In addition, the selection of indicators relies on knowledge derived from European projects addressing Soil Quality in an agricultural context, such as LANDMARK H2020 project (grant agreement No 635201) in which knowledge from Africa initiatives can be integrated. Following this introduction, the report is organised in three additional sections:

- Section 2: briefly summarises the stakeholder requirements as highlighted in the deliverable 2.1 of WP2.
- Section 3: considers the terminology, design and structure of soil information systems and briefly describes the LANDMARK methodology.
- Section 4: interprets the user requirements, described in D2.1 and summarized in section 2, in the light of the considerations made in section 3. This perspective is then used to make recommendations on the selection of parameters for the SIS. Recommendations are made separately for the 20,000 baseline sites and for the 250 reference sites. Lists of parameters are proposed for baseline and reference sites and the methodology to quantify soil quality indicators are briefly described.

2. Overview of user requirements: activity 2.1

The opinion of a large range of African stakeholders on the structure and use of a suitable SIS was captured by the activities of WP2 and are described in the report deliverable 2.1. Stakeholders were drawn from expert listings of various agriculturally based research/application groups in Africa and represent a range of activity sectors including agricultural production systems, nature preservation, water regulation, agri-business, applied research and extension, university and tertiary education, public sector and NGO/consultancy.

Their opinion was captured using a semi-structured questionnaire. The questionnaire was completed by 184 respondents, with more than 75% representing research-related activities, and the rest contributing to policy making, commodity production and marketing and advisory services. The questionnaire identified the different uses that the range of stakeholders may require from the SIS and these needs were classified in 3 categories defining overall use cases: 1) governance, 2) knowledge generation and 3) operational use. The report (D2.1) captured a variety of opinions on a range of soil quality issues per use case category, and associated stakeholder type, and also provided an overview of the requirements for a relevant SIS in Africa. The questionnaire invited opinions to be expressed about useful parameters to be included in a SIS, critical Soil Quality issues to be addressed and the relative importance of different soil functions.

Soil Quality: issues, indicators and proposed parameters

In D2.1, the Soils4Africa project asked stakeholders to define which Soil Quality issues were of greatest importance in an African context. This resulted in a large list of soil quality related issues (Table 1).

The role of organic carbon in soils and its availability was considered of primary importance. This is not surprising as many soils in African agroecosystems are very low in C content (< 1%), which results in low microbial activity and physical disruption of the soil, with soil sealing, soil crusting, low porosity, low water infiltration and low nutrient availability. Therefore, rebuilding C content is the first necessary step in rebuilding fertility and improving primary productivity and yields (Lal, 2004) can be seen at the heart of the twinned challenge considering the insufficiency of readily available biomass. Low nutrient availability is also a critical issue which relates with the low C content and affects primary productivity in the African context. Excessive alkalinity can also be a severe problem, particularly in North and North East Africa. Acidity occurs mainly in humid regions, including much

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of the highlands, and limits rootability as well as phosphorus availability from soil and fertilisers. Nutrient availability is a major problem in most of the regions of Africa, either inherently due to parent material and highly weathered soils or soil management practices whereby soil nutrients are not replenished while fallow periods are shortened. For example, in the highlands of Ethiopia most of the soils are inherently very fertile but nutrient mining of agricultural soils, including the use of manure as fuel, is one of the major reasons for declining and poor productivity relative to potential productivity. This results in a large yield gap in many parts of Africa, except on shallow or stony soils, due to nutrient shortages. The term Soil Quality was originally defined as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994, 1997). This concept has been met with much support and criticism over the years, as it is often considered difficult to quantify. However, the issue of soil quality or more recently soil health (Pankhurst et al., 1997) provides a useful communication tool to stakeholders and society on the complex interactions which take place in the soil to support a range of ecosystem functions (Powlson, 2020). Powlson (2020) suggests that the terms of Soil Quality and Soil Health are synonymous from the perspective of scientific quantification and therefore throughout this report we refer to Soil Quality but this includes Soil Health and can be seen as in analogy with the concept of land quality of the framework of land evaluation (FAO, 1976; Driessen and Konijn, 1992; IIASA/FAO, 2012). It is important to note that numerous studies exist on soil quality and soil health indicators within a context of sustainability and productivity of agriculture in Africa, and globally,providing relevant insight in the causes, and possible solutions, of declining soil quality in Africa. These studies though refer to numerous concepts using different terminologies (de Ridder and van Keulen, 1990; Leenaars, 1990; Pieri, 1992; Lompo et al., 1995-2020; Driessen, 1997; Eswaran et al., 1997; Seybold et al., 1997; Leenaars, 1997; Dumanski and Pieri, 2000; Bationo et al., 2003, 2007, 2012, 2015; FAO, 2011; Chinau et al., 2011; Kintche, 2011; Fairhurst, 2012; Cardoso et al., 2013; Andriesse and Giller, 2015; FAO and ITPS, 2015; Tully et al., 2015; FAO, 2016; Takoutsing et al., 2016; Hengl et al., 2017; Griffiths et al., 2018; Ball et al., 2018; Kihara et al., 2020; Jian et al., 2020; CABI-ASHC, 2021; World Bank, 2021).

Interestingly, the term soil functioning was lower down on the list of soil quality associated issues, but encompasses many of the other issues listed. The term, like soil quality and soil health, is perhaps too broad when considering the application of a Soil Information System. The following sections will

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explain an approach by which soil multi-functionality (addressing many of these soil quality issues) can be further refined and applied to the data collected within the Soils4Africa SIS.

Table 1. Table reproduced from D2.1. Relevant Soil Quality Issues for SIS according to the stakeholders.

Soil Quality Issues	Percentage
Rootability	33.7
Sodicity	35.3
Soil functioning	36.4
Workability	39
Availability of soil volume (foothold) and of topsoil	43.3
Permeability	43.9
Aeration	47.6
Toxicity	49.7
Agricultural intensification potential	49.7
Infiltrability (surface permeability)	51.3
Salinity	52.9
Alkalinity	55.6
Porosity	59.9
Nutrient balance (ratios)	63
Water availability	63.6
Agricultural suitability	70.6
Soil quality status	72.2
Soil health	72.7
Nutrient availability	75.4
Acidity	75.9
Organic carbon (SOC) availability (feed for microbes)	77

Soil functions

Andrews et al. (2004) tried to further refine the concept of soil quality as “the capacity of a soil to function”; functions should include the role of soil in supporting water flow and retention, solute transport and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of potentially toxic materials and maintenance of biodiversity and habitat. Over the years, these have been further refined and a common set of five agricultural soil functions are now considered: (1) support of primary production, (2) water purification and regulation, (3) carbon sequestration and climate regulation, (4) soil biodiversity and habitat provisioning and (5) recycling of nutrients (Haygarth and Ritz, 2009; Schulte et al., 2014). Vogel et al. (2018) suggested that pest control and pollutant degradation should be considered as two additional soil functions. There is scope in the Soils4Africa project to include those two functions in the assessment, as suggested by the inclusion in the proposal of measurements of pollutant (heavy metals, pesticide residues) and chemical pest control (pesticide residues).

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In D2.1, stakeholders were asked to score the importance of the five soil functions in terms of current uses of the soil. Overall, users expressed interest in all 5 soil functions mentioned above and accorded similar importance to each of them. This was the case across stakeholder types (Figure 1) as well as within different activity sectors and use cases (see D2.1).

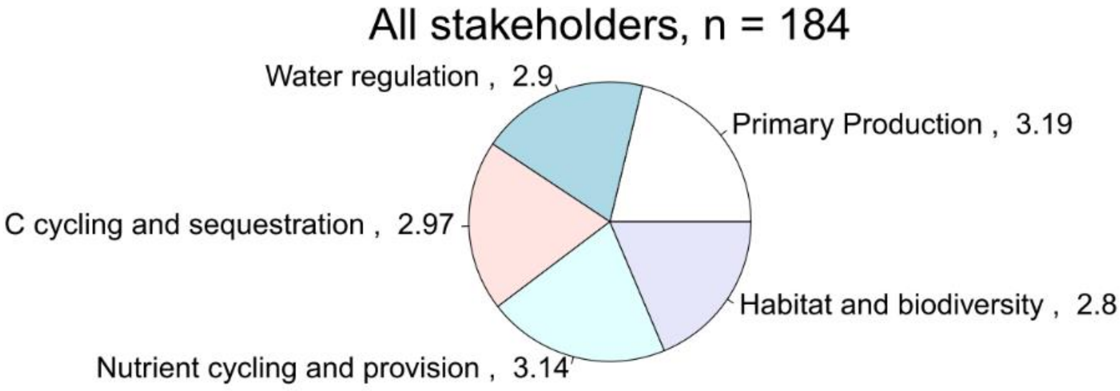

Figure 1. Figure copied from deliverable 2.1. Key soil functions that define the content of the SIS. ***.*** *Each stakeholder was asked to grade from 1 to 5 each of the five functions so that the sum of the five grades would equal 15. For the cases for which the sum of grades was different than 15, the scores were normalized to bring this sum to 15 while keeping the relative proportion of each function to the total constant (Normalized score = (score x 15) / sum of scores).*

The specific user requirements for each function define a *demand* for functions. In D2.1, demand was identified and categorised as three use cases (or stakeholder categories) (Table 2). The demands placed by these stakeholders for soils information pertaining to soil functions are as follows:

1) Governance – this requires a range of information related to the overall sustainability of a system/land use: (i) how soil/land-use combinations may vary in their capacity to support a range of soil functions, (ii) which land management practices suppress multi-functionality, (iii) which single functions may/should be prioritised and at what scale, for example climate change policies both at a country and global scale. From a soil data perspective, policy makers are requiring information not on single soil properties or attributes but rather wish to understand the capacity of soils to support a range of, or specific functions for a given region.

2) Knowledge generation and transfer – this requires information and training on understanding how we can utilise existing data to support the development of advice and new tools to quantify and assess changes in the supply of soil functions. The Soil Information System will be important in informing future research developments on quantifying soil functions for a range of land uses across

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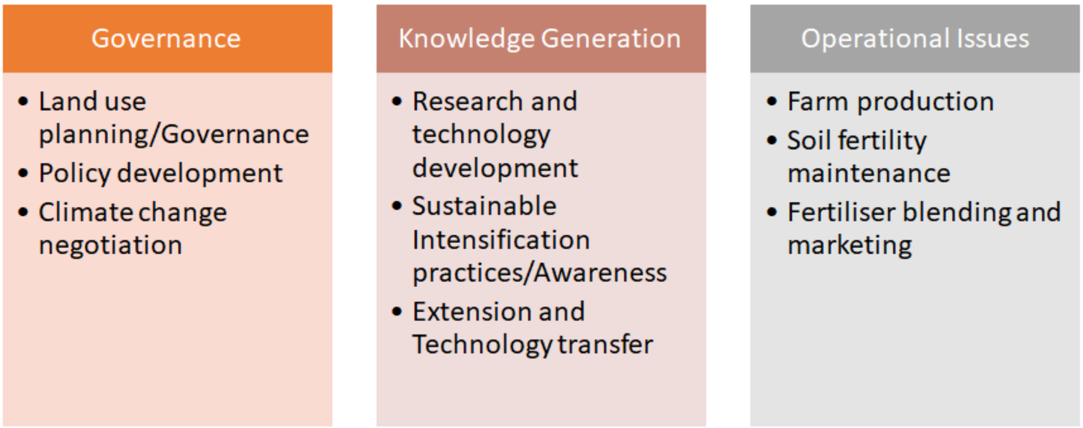
Africa. This has not yet been achieved and needs basic soil information at a pan-African scale to provide a baseline for future developments.

3) At farm or production level, the focus remains on operational issues and is equated to optimising the capacity of certain soil functions through management practices. Here, farmers and advisors need better access to soil information to better understand and manage their soil resources. This may be to optimise nutrient cycling in the Ethiopian context given above, where nutrient mining has left the soils bereft of fertility and has also resulted in lowered productivity. By optimising the nutrient cycling function through specific management practices, such as fertilisation, organic matter inputs (such as manure or residues) and reduced tillage, optimisation can be achieved over time.

Table 2. Table reproduced from D2.1. Grouping of Soil Information needs for use case development.



Governance	Knowledge Generation	Operational Issues
• Land use planning/Governance • Policy development • Climate change negotiation	• Research and technology development • Sustainable Intensification practices/Awareness • Extension and Technology transfer	• Farm production • Soil fertility maintenance • Fertiliser blending and marketing

3. Structure and terminology of Soil Information Systems

Partial glossary for the Soil Information System

Soil Quality, Soil Health, Functions, Parameters, Indicators, Characteristics, Qualities, Attributes are terms commonly used in the context of different SIS and land evaluation systems (Figure 2). Some of these terms have been used with different meanings in different contexts, and different terms can also be used with similar meanings in different SIS (example in Figure 2). A clear terminology is therefore of paramount importance.

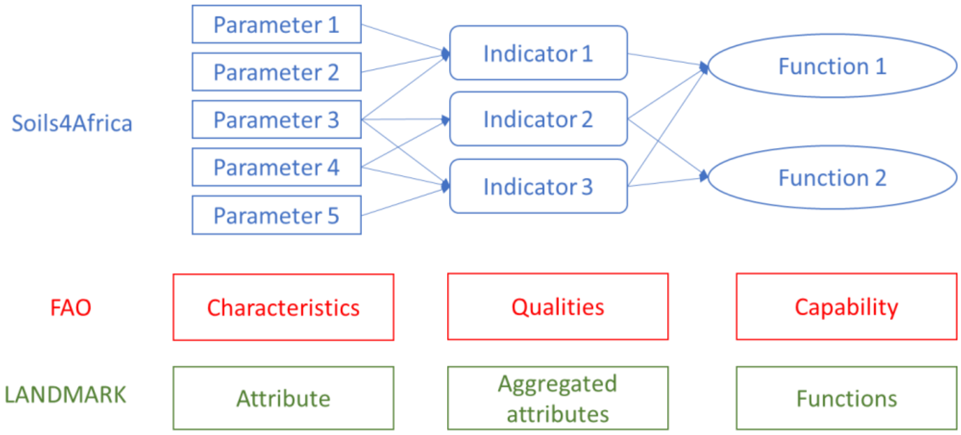


Figure 2. Schematic representation of a SIS design and equivalence between terminologies in different programmes: Soils4Africa in blue, FAO land evaluation framework in red and LANDMARK in green.

Here we provide a partial glossary of the terms used in the Soils4Africa project. The definitions stem from an analysis of the literature have been adapted from the terminology and the structural design of the LANDMARK project. Detailed explanation for these definitions can be found in Annex 1.

Parameter

An instrument (measurement, model, expert elicitation system) for quantifying a function. Parameters can quantify soil physical, chemical and biological properties, climatic and environmental conditions, land use and management characteristics.

Integrated parameter

An element of a hierarchical organisation (a decision tree model) linking parameters to functions that combines information from a set of parameters and constitute a part of a higher level of integration in the classification. In the LANDARK terminology, this is referred to as *aggregated attribute*.

Indicator

The highest level of integrated parameters. Indicators are quantified using a set of parameters and integrated parameters through a decision tree model and are used in the scoring of a function.

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Soil function = Soil based ecosystem service

An overarching concept referring to one elemental aspect of the soil system that contributes to the generation of goods and services. For Agriculture and Forestry, these comprise**:** (1) primary productivity, (2) water purification and regulation, (3) carbon sequestration and climate regulation, (4) provision of habitat for intrinsic and functional biodiversity, (5) nutrient cycling. Soils vary hugely in their capacity to provide certain functions. Therefore, functions must be defined relative to the maximum capacity of the system to deliver this function in a reference situation. We refer to this maximum capacity as "*potential functionality*". The potential functionality is defined by specific conditions of land use (U), climate (C), and pedology (P). The supply of a function is the distance between actual functionality and potential functionality. It is adjustable through management and assessed and monitored using a soil information system.

Therefore, a function F is scored relative to the potential functionality, itself defined by local conditions (U, C, P). The score (function supply) depends on management:

$$F_{u,c,p} = f(\mathit{management\ options})$$

Soil Quality = Soil Health

Following recent reviews and conceptual papers (Bünemann et al., 2018; Powlson, 2020), the two terms are considered equivalent. They are defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. It can be scored relative to the set of five functions and defined relative to them as the degree to which a soil can perform its soil functions. The concept of overall soil quality can therefore be understood/quantified as a score of multifunctionality, a combination of the scores of each individual function.

Further considerations on the supply of soil functions

As described above, soil functions are evaluated and expressed as the supply of the function by the soil relative to a maximum capacity: the potential functionality. Soils differ in their relative capacity to perform each function (Coyle et al., 2016). This capacity to perform a given function depends on a set of factors including the climatic environment and pedogenetic characteristics (typically characterised by soil type, soil depth, slope, mineralogy and/or soil texture).

It is critical to note that agricultural management is the main pathway to managing soil functions. It is uniquely through changes in agricultural practices that soil properties can be altered and stirred towards an improvement of supply of soil functions, and therefore of Soil Quality. If a SIS is designed to monitor and evaluate Soil Quality with the aim of evaluating the sustainability of changes in agricultural practices, as is the case of Soils4Africa, recording management information is a requisite. Repeated measurement of soil parameters over time will allow characterisation of the function supply relative to potential functionality (e.g. in a given set of conditions of land use, climate and pedology), but will be insufficient to understand what management practices result in the change of Soil Quality for each condition and therefore will lack the information necessary to inform on what management practices constitute the set of solutions leading to sustainable intensification.

The LANDMARK approach

Generalities and brief description of the method

The LANDMARK project assesses Soil Quality by scoring the five soil functions defined above: (1) primary production, (2) water purification and regulation, (3) carbon sequestration and climate regulation, (4) soil biodiversity and habitat provisioning and (5) recycling of nutrients. Each function is scored based on the measurements of a set of soil parameters (called *attributes* in the LANDMARK system) in combination with management characteristics and environmental conditions. The assessment (score) of soil functions can be modelled using a set of input parameters which will form the basis of hierarchical decisions models (or decision tree models) including several levels of integration (Debeljak et al., 2019), instead of the dichotomic model presented in Figure 2. Any two parameters that need to be integrated form together a higher level in the hierarchy and the levels between parameters and functions are defined as *integrated parameters (integrated attributes* in the LANDMARK project*).* These models have been successfully applied in a European context) and are currently being applied in China, S. America and Ethiopia for specific land-uses. Examples of the European models for Carbon and Climate Regulation (Van de Broek et al., 2019) and Primary Productivity (Sandén et al., 2019) are provided in Annex 2 and 3, respectively.

The hierarchical structure of the decision tree models (the exact linkages) are formed using a qualitative approach to multi-criteria decision modelling (MCDM) called the Decision Expert (DEX) integrative methodology. Multi-criteria decision modelling aims at structuring and solving decision problems (scoring soil functions in our case) that involve multiple and possibly conflicting criteria using relatively simple, readily available information (the parameters) (Bohanec, 2017). The DEX methodology is a qualitative form of MCDM whose most important feature is to be *rule-based,*

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meaning that the hierarchical aggregation of parameters is defined using *decision rules* (Bohanec, 2017) that rely heavily on expert knowledge and existing information (Debeljak et al., 2019).

The use of LANDMARK methodology in Soils4Africa

The knowledge applied for the LANDMARK decision tree models was based on a European expertise of the European context and cannot readily suit the Soil4Africa context of a Pan-African assessment. Adapting the decision rules for each function to African contexts will pose important challenges, both related to the difficulty of relying on expert knowledge and on access and availability of existing data (which is being assessed in another work package). Soil function models would need be created for a range of African agricultural systems and thresholds would be applied according to the agroecological zone under consideration. Furthermore, the first step in the development of those decision tree models is actually to define the decision problem (the function to score). As mentioned in section 2, although they were discarded from LANDAMRK project, *pest control* and *pollutant degradation* are two functions that would be very relevant to assess in Soils4Adfrica, as clearly highlighted by the inclusion in the Sols4Africa proposal of measurements of pesticide residues and heavy metals. New decision trees for those two functions (decision problems) should be developed based on African expert knowledge defining a set of decision rules.

Nonetheless, the Soil Information System has the capacity to support the future development of these models for a pan-African context. Therefore, in addition to the assessment of soil quality indicators defined based on the user-defined (in D2.1) critical soil quality issues (see next section), we recommend collecting basic information relating to soil functions at the 20,000 baseline sites, and to use the 250 reference sites to collect information that will allow developing decision tree models adapted to African contexts for some of the soil functions supporting the assessment of overall Soil Quality based on soil multifunctionality in a pan-African evaluation.

4. Recommendations

In this section, we provide a line of sight for the utilisation of the Soils4Africa Soil Information System to enable the assessment of soil functions and multifunctionality for a range of agricultural systems across Africa. However, constraints in terms of feasibility, site access and available material make it unrealistic to measure such a large set of parameters at as many as 20,000 sites using harmonised and consistent methodology by a range of operators. It was also incidentally required by the stakeholders that the set of measurements should be manageable and use accessible methodologies.

Therefore, to meet the ambitious requirements from stakeholders while considering practical constraints defining feasibility, we argue that different recommendations should be provided for the two site subsets: the full set of 20,000 sites on one hand, and the 250 reference sites on the other hand. In brief, we recommend collecting parameters necessary to quantifying potential functionality for each of the five functions at the 20,000 sites as a baseline reference for the assessment of multifunctionality. This will require general land use types and climatic information, as well as a few soil parameters (Table 4) (mostly chemical and physical). This set of parameters is minimal and can be expanded while remaining within a feasible sampling and analysis strategy. In addition to this information relating to the multifunctionality, additional parameters necessary to the assessment of a range of indicators directly responding to the soil quality issues highlighted in D2.1 (but not necessarily directly related to the soil functions, although most will) will be recommended (Table 3). Measurements of these parameters (in addition to those in Table 4) at the 20,000 baseline sites will represent the first set of measurements defining a time-0 baseline assessment for the monitoring of the soil quality indicators most directly related to pressing soil quality issues as defined in D2.1, according to procedures such as land-use systems analysis by means of e.g. land evaluation or crop modelling. The selected indicators and the parameters needed to assess them are presented in Table 5. These soil quality indicators do not necessarily feed into the evaluation of soil functions within the described landmark framework, leading to an overall score for soil quality, but serve as input to evaluate intensified agricultural productivity relative to potential productivity. Finally, for the 250 reference sites, we recommend a comprehensive list of parameters, including soil physical, chemical and biological parameters, as well as detailed management and environmental parameters (Table 6). Overarching motivation for such a comprehensive list is the opportunity to use this subset of 250 sites as the first time point in a time series aiming at monitoring Soil Quality (in the broad sense defined in the glossary, e.g. related to soil multifunctionality) at sites representative of the range of land uses and pedoclimatic conditions across Africa. This will help to evaluate and finally identify agricultural management practices leading to good Soil Quality and information on future management designs for sustainable intensification. The list presented here, however, is too extensive and unsuited to the project for practical reasons and for cost considerations. The table aims at serving as a basis for adaptation of the LANDMARK's decision tree model to the conditions in Africa and investigate the parameters that need to be included in the minimum set of parameters to record at the reference sites (see next section).

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The tables 3, 4, 5 and 6 introduced here are presented in the sub-sections below, together with some further explanations for the inclusion of specific parameters and/or parameter categories.

Full parameters list for 20,000 baseline sites

Table 3. Full parameters list for the 20,000 baseline sites. It contains the list above and adds a set of important parameters that are considered feasible at the 20,000 sites. In red are in indicated the parameters included in the Soils4Africa proposal.

Parameter
Annual precipitation **
Precipitation (cropping season) **
Precipitation (wet season) **
Annual temperature (and evaporation) **
Altitude **
Slope degree
SOC
Extractable P (C:N:P)
Total N (C:N)
Texture (sand, silt, clay)
pH
Soil crusting/sealing (incl. surface roughness)
Drainage class
Depth of soil to groundwater table
Depth of soil (to bedrock or induration)
Rootable depth of soil (to observed constraint to rooting)*
Heavy metals (incl. cadmium)
Carbonate content
Bulk density*
Electric conductivity (salinity)
CEC
Effective CEC (sum of exchangeable bases and acidity)
Extractable nutrients (= available nutrients) incl. exch. bases (K)
Exchangeable acidity
P fixation
Total elements
Coarse fragments volumetric
Climate information **
Land use information including management intensity regime

* Bulk density will not be measurable at many sites. We recommend estimating bulk density at each of the 20,000 sites where possible from other parameters using pedotransfer functions (PTF). Similarly, we recommend inferring rootability and rootable depth, for a reference crop, from other parameters using decision rules.

** Data obtained from auxiliary data sources.

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Parameters defining potential functionality

The following list represents the set of necessary and sufficient parameters to quantify potential functionality. This is a subset of the list for the 20,000 baseline sites. It is indicated to which functions each parameter contributes defining the potential functionality.

Table 4. Minimum parameters list for the 20,000 sites. These are the parameters necessary to define the potential functionality for each function. In red are in indicated the parameters included in the Soils4Africa proposal.

Parameter	**Primary Productivity**	**Water regulation**	**Nutrient cycling**	**Climate Regulation**	**Biodiversity**
Annual precipitation	x	x	x	x	x
Precipitation (cropping season)		x			
Precipitation (wet season)		x			
Annual temperature	x			x	x
Altitude	x				
Slope degree	x				
SOC	x	x			x
P (C:N:P)	x	x	x		x
N (C:N)	x			x	x
Texture	x	x	x	x	x
pH	x		x	x	x
Soil crusting		x			
Drainage class		x	x		
Depth to groundwater table	x	x	x		
Depth to bedrock	x		x	x	
Rootable depth	x	x	x	x	
Bulk density	x	x	x		x
CEC	x		x		
Coarse fragments	x	x	x		

Soil quality indicators for user-defined soil quality issues

Table 3. List of soil quality indicators assessing the soil quality issues identified in deliverable 2.1. The parameters necessary to assess each indicators are also listed and references provided indicate the methodology to convert measured parameters into indicator assessment.

Soil quality Indicator	Parameters	Reference
Water availability	Annual precipitation and evaporation, Groundwater depth, Soil depth (and rootable depth), Coarse fragments, Water retention (ptf: Texture, SOC, Bulk density, Porosity), Infiltration (crusting/sealing)	Leenaars et al., 2018; Driessen and Konijn, 1992; IIASA/FAO, 2012; Sys et al., 1991
Nutrient availability	Stock, retention, release: CEC, texture, SOC, Extractable (available) nutrients, Exchangeable nutrients (Ca, Mg, K), pH, P retention, Total elements	Sanden et al., 2019; Fischer et al., 2008; 2012; Sys et al., 1991
Oxygen availability	Porosity, drainage class, groundwater depth	Fischer et al., 2008; 2012
C sequestration potential	SOC, Bulk density, Coarse fragments, Texture	Van de Broek et al., 2019
Microbial activity	SOC, pH, total elements, C/N, labile SOC	Sanden et al., 2019
Workability	Surface stoniness, stickiness, slope	IIASA/FAO, 2012
Toxicity	Exchangeable acidity, heavy metals (cadmium), calcium carbonate, gypsum, CEC	IIASA/FAO, 2012
Filtering/Buffering	CEC, Coarse fragments, pH	Calzolari et al., 2016
Erodibility/Erosion	Infiltration capacity, soil surface roughness, soil surface crusting/sealing, soil water storage capacity, SOC, Coarse fragments, Bulk density, Texture, Slope, Landcover	Chen et al., 2018
Salinity	EC	IIASA/FAO, 2012
Sodicity	Exchangeable Na, CEC	

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Porosity	Bulk density, texture, SOC	
Rootability	Porosity, acidity, alkalinity, sodicity, salinity, toxicity, textural profile homogeneity, oxygen availability, compaction/induration/ bedrock	Leenaars et al., 2018; IIASA/FAO, 2012

Full parameters list for 250 reference sites: monitoring functions supply

The following list is adapted from the list developed in the LANDMARK project to score all five soil functions. This list can serve to define both potential functionality as well as scoring the actual supply of each and all functions in a European context. We want to base ourselves on this approach for the development of measurable indicators for soil functionality. The list of parameters that are considered below is quite extensive and it is, for practical reasons and for cost considerations, impossible to record these within the context of the Soils4Africa project. Therefore we will adapt the decision tree model to the conditions in Africa and investigate the parameters that need to be included in the minimum set of parameters to record. Particularly, soil biological indicators are difficult to quantify at remote sites due to obvious difficulties in transporting and storing fresh and/or frozen soil samples. If these technical challenges can be overcome, we recommend quantifying the biomass and abundance of at least two faunal groups (for example, nematodes and macrofauna, or earthworms or termites), as well as bacterial and fungal biomass based on DNA amplification. If frozen samples can be stored, the extracted DNA can potentially serve later for metagenomics analysis or quantification of functional genes using qPCR, as has been applied in the recent LUCAS-Topsoil survey (Orgiazzi et al., 2018). A comprehensive set of soil biological parameters is in table 6. For management parameters, the list is now largely unadapted to African context and is therefore only indicative. The actual parameters to be recorded will depend on the final selection criteria of the 250 reference sites (e.g. the land use type).

Table 6. Parameters list for the 250 reference sites. These parameters are additional to the list for the 20,000 sites. The whole set of parameters (this table + table 3) parameters can be used to define the supply of each function relative to their potential functionality.

Paramater type	**Parameter**
Soil physico-chemical	Bulk density*
Soil physico-chemical	Labile SOC
Soil physico-chemical	Pesticide residues in soil
Soil physico-chemical	Soil organic matter
Soil physico-chemical	Soil diagnostic horizons, properties, materials (WRB)
Soil physico-chemical	Soil class (WRB RSG & PQs and SQs)
Soil physico-chemical	Thickness of organic layer
Soil biological	Rooting density
Soil biological	Bacterial biomass

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Soil biological	Earthworm abundance
Soil biological	Earthworm richness
Soil biological	Enchytraeid abundance
Soil biological	Enchytraeid richness
Soil biological	Fungal biomass
Soil biological	Microarthropod abundance
Soil biological	Microarthropod richness
Soil biological	Nematode abundance
Soil biological	Nematode richness
Soil biological	Rhyzobium abundance
Soil biological	Mycorrhiza abundance
Environment	Average daily temperature in first month of growing season
Environment	Groundwater table depth
Environment	Number of days with daily average temperatures above 5^{o}C
Environment	Precipitation - Cropping season
Environment	Precipitation - Wet season
Environment	Precipitation in first month of growing season
Environment	Slope
Management	Ammonia share of waste
Management	Artificial drainage
Management	Biological pest management
Management	Catch crops
Management	Chemical pest management (pesticides)
Management	Cover crop
Management	Crop failure risk
Management	Crop residue management
Management	Crop type (Water used by crop type)
Management	Drained peatland
Management	External C inputs
Management	Fraction of annual yield harvested via grazing
Management	Grassland
Management	Grassland in rotation
Management	Incorporation of by-product (e.g. manure, compost, sludge)
Management	Irrigation
Management	Irrigation frequency
Management	Irrigation rate
Management	Irrigation type (H_2O efficiency)
Management	Labile Carbon input
Management	Liming
Management	Manure application
Management	Manure type
Management	Mineral N fertilisation
Management	Mineral P fertilisers input
Management	N fertilization (Organic & Mineral)

Management	N offtake by crop
Management	NH4 content in manure
Management	Nitrification inhibitors
Management	NPP yield
Management	Number of crops in rotation
Management	Organic N fertilisation or export
Management	Organic N fertilisation (manure) or export
Management	Organic P input or export
Management	Percentage of catch groups, cover crops, green manure (CaC/CoC/GM)
Management	Percentage of legumes in rotation
Management	Physical pest management
Management	Share of catch or cover crops
Management	Share of crop residues left in the field after harvest (%)
Management	Share of legumes (number of years out of 5 previous years - excluding present year)
Management	Stocking rate
Management	Tillage
Management	Type of crops in rotation
Management	Yield

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ANNEXES

Annex 1: Considerations on the terminology

The terminology and concepts surrounding Soil Quality have been under debate for decades and are still evolving, explaining why its operationalization (the design of SIS) is still a challenge (Bünemann et al., 2018; Lehmann et al., 2020). Bünemann et al. (2018) extensively reviewed the literature on Soil Quality to conclude that it can be defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans". For agro-ecosystems, this holistic view of Soil Quality can be operationalized around the five soil functions defined above in that those functions capture the capacity of soils to support ecosystem services and therefore sustainability. Therefore, soils that score high on all functions have a high quality, while poor quality soils score poorly on several functions (Schulte et al., 2014).

The term *function* carries its controversies. Functions can refer to bundles of soil processes used in the assessment of ecosystem services (Bünemann et al., 2018), or can be defined at the highest level as being equivalent to a subset of ecosystem services: the 'soil based ecosystem services' (Schulte et al., 2014). The latter is the definition retained in this report, with the five functions or 'soil-based ecosystem services' as defined above considered to capture all aspects of Soil Quality.

The term *indicator* is often used in the terminology as an intermediary between parameters and functions. Parameters, indicators and functions can simply be organized in a hierarchical tree with three fixed levels (Figure 2). Parameters are measured properties of the system which can be grouped together to quantify or score indicators, which themselves can be grouped to finally score functions. One or more parameters are needed to quantify an indicator and parameters can be used in the quantification of several indicators. Similar hierarchical trees have been built in other projects using different terminologies, with for example the FAO land evaluation framework defining land characteristics, land qualities and suitability, evaluated relative to land use requirements with similar meanings to those described above for parameters, soil quality indicators and functions, respectively. The LANDMARK project has developed yet another system where a concept close to parameter is defined as an attribute, which can be aggregated to quantify not indicators but simply aggregated attributes (Figure 2).

Overall, different words are used to convey related (but not always identical) meanings in SIS with similar structures. In addition to that, the meaning conveyed by given words can vary significantly

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between papers, projects, SIS, etc... *Parameters* are relatively easy to define and include any soil physical, chemical or biological property that can be measured. Yet, it is not clear whether only soil properties should be included as parameters in a SIS or whether environmental and management information should also be included as parameters. For example, the parameters for the LUCAS Topsoil soil survey are limited to soil parameters and any other input is considered as metadata while the LANDMARK project includes several types of parameters (defined as *attributes*) including management, environmental and soil attributes directly in the first level of the SIS organisation. *Indicators* are even more difficult to define. Bünemann et al. (2018) proposed that any sensitive soil attribute that reflects the capacity of the soil to function can be used as an indicator of Soil Quality. Beyond their relevance to Soil Quality (relevance to at least one soil function), indicators should satisfy several criteria, including sensitivity (changing detectably and quickly without reflecting merely short-term oscillations), practicality (cheap and easy to implement with a short-turnover time), and informativeness for management (Lehmann et al., 2020). Many currently used indicators do not meet these four criteria, including some of the most used indicators like soil organic carbon (Lehmann et al., 2020). Moreover, it is difficult to evaluate to which extent some parameters can directly be used as indicators and which require to be bundled to define meaningful indicators. For example, Lehmann et al. (2020) list soil organic carbon and biodiversity as desirable indicators for monitoring Soil Quality. While proper assessment of biodiversity would require a set of different parameters to be quantified or scored, soil organic carbon can easily be estimated from a single measurement and can therefore be considered as a parameter. Constraining the SIS design on a dichotomic separation of parameters and indicators therefore involves binary choices that may often be somewhat arbitrary. This is why the structural SIS design developed in the LANDMARK project has been retained here. Each function is scored based on the measurements of a set of parameters (called *attributes*) which regroup any measurement of a property characterising the system at a given time, including soil properties, management characteristics and environmental conditions. The link between quantified parameters and functions is based on a hierarchical decision tree model including several level of integration instead of the dichotomic model presented in Figure 2. Any two parameters that need to be integrated together form a higher level in the hierarchy and the levels between parameters and functions are defined as *integrated parameters (integrated attributes* in the LANDMARK project*).* We define here the highest level of integration as *indicator*. Two examples of

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hierarchical LANDMARK models, for the climate regulation function and the primary productivity, are presented in Annexes 2 and 3.

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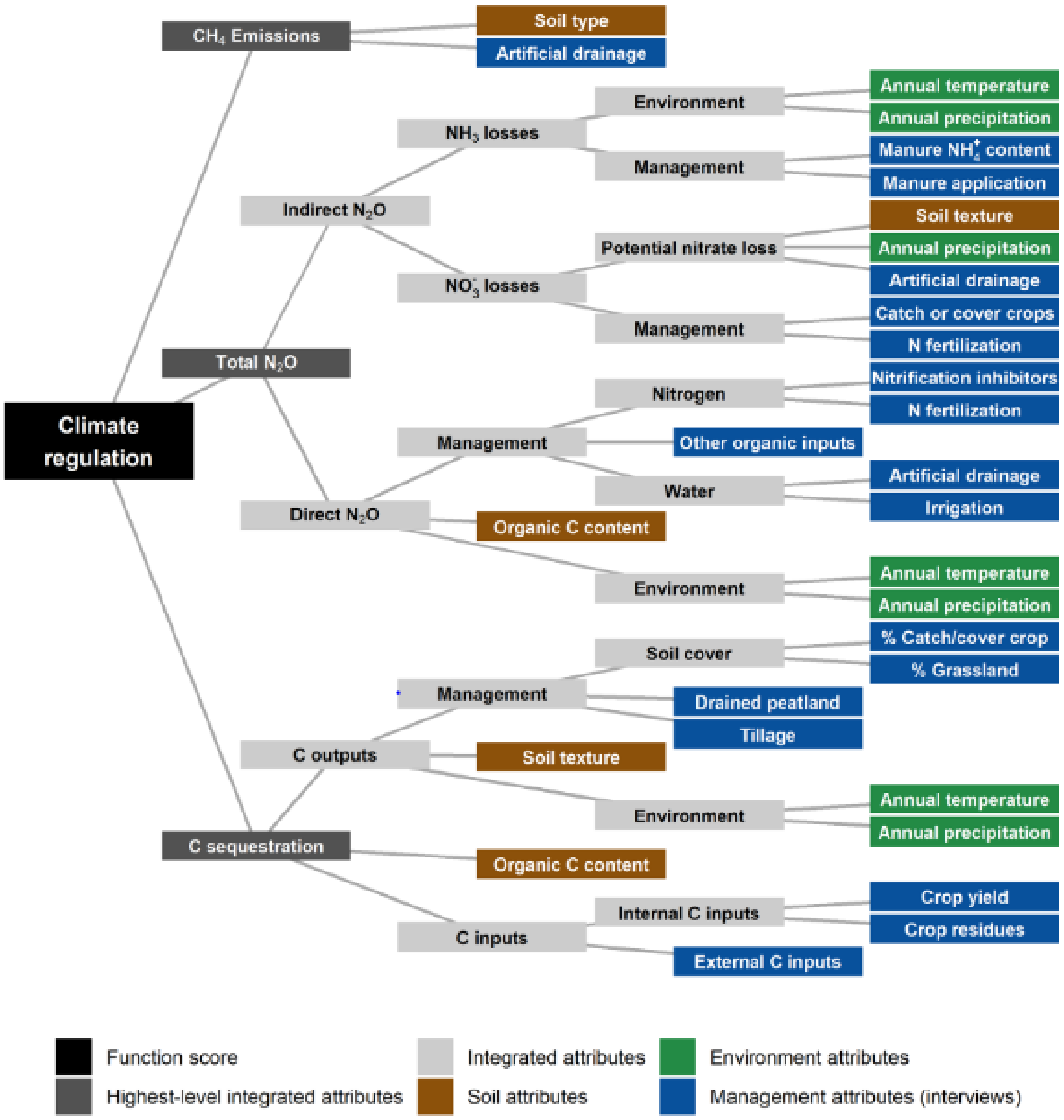
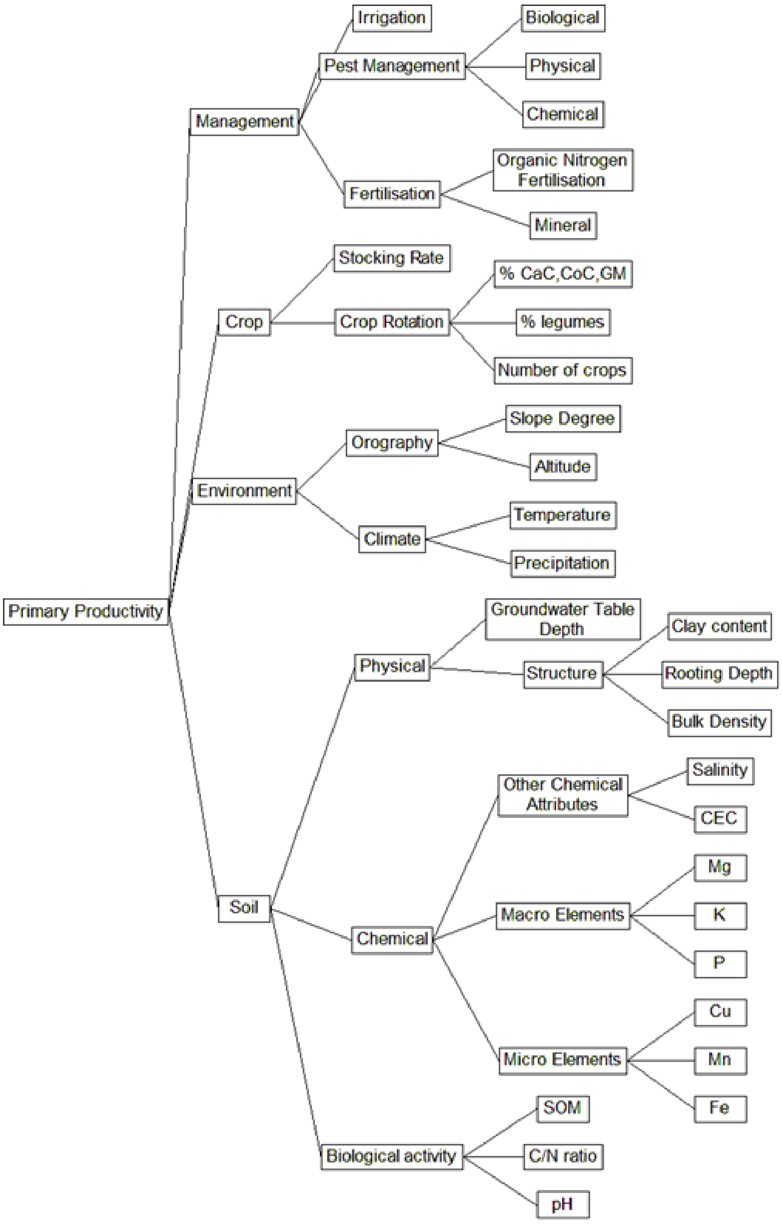
Annex 2: LANDMARK decision tree: example of the climate regulation function

Example of the decision tree model used in the LANDMARK project to score the climate regulation function. The exact hierarchical structure was developed for Europe and is only indicative here. It would need to be adapted to be used in monitoring Soil Quality in Africa. The set of parameters used at the basis of this tree provides, however, a sensible set of parameters to be measured at the 250 reference sites to provide the baseline for starting Soil Quality monitoring.



Annex 3: LANDMARK decision tree: example of the primary productivity function

Example of the decision tree model used in the LANDMARK project to score the primary production function. The exact hierarchical structure was developed for Europe and is only indicative here. It would need to be adapted to be used in monitoring Soil Quality in Africa. The set of parameters used at the basis of this tree provides, however, a sensible set of parameters to be measured at the 250 reference sites to provide the baseline for starting Soil Quality monitoring. Figure reproduced from Sanden et al. (2019).



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