Semantics about soil organic carbon storage: DATA4C+, a comprehensive thesaurus and classification of management practices in agriculture and forestry

Kenji FUJISAKI[1], Tiphaine CHEVALLIER[2], Antonio BISPO[1], Jean-Baptiste LAURENT[3,4], François THEVENIN[5], Lydie CHAPUIS-LARDY[2,6], Rémi CARDINAEL[3,7,8], Christine LE BAS[1], Vincent FREYCON[9,10], Fabrice BENEDET[9,10], Vincent BLANFORT[11,12], Michel BROSSARD[2], Marie TELLA[13,14], Julien DEMENOIS[3,15,16]*

1 INRAE, Info&Sols, 45075, Orléans, France
2 UMR Eco&Sols, IRD, INRAE, CIRAD, Institut Agro, Univ Montpellier, Montpellier, France
3 AIDA, Univ Montpellier, CIRAD, Montpellier, France
4 CIRAD, UPR AIDA, 34398 Montpellier Cedex 5, France
5 Société Khaméos
6 LMI IESOL, Dakar, Sénégal
7 CIRAD, UPR AIDA, Harare, Zimbabwe
8 Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe
9 Forêts & Sociétés, Univ Montpellier, CIRAD, Montpellier, France
10 CIRAD, UPR Forêts & Sociétés, F-34398 Montpellier, France
11 SELMET
12 CIRAD, SELMET
13 US Analyses, Univ Montpellier, CIRAD, Montpellier, France
14 CIRAD, US Analyses, 34398 Montpellier Cedex 5, France
15 CIRAD, UPR AIDA, Turrialba 30501, Costa Rica
16 CATIE, Centro Agronómico Tropical de Investigación y Enseñanza, Turrialba 30501, Costa Rica

*correspondence to : Julien Demenois (julien.demenois@cirad.fr)

Abstract

Identifying the drivers of soil organic carbon (SOC) stock changes is of utmost importance to contribute to global challenges like climate change, land degradation, biodiversity loss or food security. Evaluating the impacts of land-use and management practices in agriculture and forestry on SOC is still challenging. Merging datasets or making databases interoperable is a promising way but still with several semantic challenges. So far, a comprehensive thesaurus and classification of management practices in agriculture and forestry is lacking, especially while focussing on SOC storage. Therefore, the aim of this paper is to present a first comprehensive thesaurus for management practices driving SOC storage (DATA4C+). The DATA4C+ thesaurus contains ~~226~~ 224 classified and defined terms related to land management practices in agriculture and forestry. It is organized as a hierarchical tree reflecting the drivers of SOC storage. It is oriented to be used by scientists in agronomy, forestry and soil sciences with the aim of uniformizing the description of practices influencing SOC in their original research. It is accessible in Agroportal (http://agroportal.lirmm.fr/ontologies/DATA4CPLUS) to enhance its findability, accessibility, interoperability and re-use by scientists and others such as laboratories or land managers. Future uses of the DATA4C+ thesaurus will be crucial to improve and enrich it, but also to raise the quality of meta-analyses on SOC, and ultimately help policy-makers to identify efficient agricultural and forest management practices to enhance SOC storage.

Keywords

interoperability, data, FAIR movement, climate change, soil carbon sequestration

1. Introduction

Soil organic carbon (SOC) represents about 25% of the potential of natural climate solutions (NCS) to mitigate climate change (Bossio et al., 2020). Maintaining or increasing SOC stocks can play a significant role to tackle global challenges like climate change, but also land degradation, biodiversity loss or food security (IPCC, 2019). Identifying and addressing the drivers of SOC stock changes is therefore crucial to contribute to Sustainable Development Goals (e.g. SDGs 2, 13 and 15) adopted by the United Nations in 2015 (UN General Assembly, 2015).

Wiesmeier et al. (2019) reported a large number of drivers at various scales, from climate to soil physico-chemistry, including land-use and management practices. Land-use and management practices shape carbon inputs and outputs at the plot scale, quality of carbon inputs, and may modify the turnover of soil organic matter (SOM) and SOC stocks (e.g. Fujisaki et al., 2018; Paustian et al., 2016; Poeplau et Don, 2015; Powlson et al., 2016). Evaluating the efficiency of management practices (e.g. no tillage, organic amendments) and improving our understanding of processes involved in SOC storage is still challenging and discussed (Chenu et al., 2019; Erb et al., 2017). Consequently, large datasets are necessary to make statistically robust analysis of SOC storage and its drivers. In that perspective, the number of systematic reviews or meta-analyses is growing (e.g. Beillouin et al., 2021; Bolinder et al. 2020; Cardinael et al., 2018; Fujisaki et al. 2018). Data-driven soil research and the inference of soil knowledge directly from data by using computational tools and modelling techniques, are becoming more and more popular (Wadoux et al., 2020). Merging datasets or making databases interoperable to have global datasets is another promising way (e.g. Lawrence et al., 2020; Wieder et al., 2020). Open Science (OCDE, 2015) and the FAIR

– i.e. Findability, Accessibility, Interoperability, Reusability- guiding principles (Wilkinson et al., 2016) offer opportunities to explore this path.

However, two conditions for drivers, such as land-use and management practices, are compulsory for systematic reviews, meta-analyses or interoperability of databases on SOC storage: 1) have standard definitions and 2) be homogeneously described. Harden et al. (2018) highlighted the need for harmonized description of land-use and management practices. Todd-Brown et al. (20221) emphasized the role that semantics should play to overcome the challenges above. Indeed, there are currently two major limitations for these drivers of SOC change: subjectivity of the semantics and limited scope of the terms. Many global scale studies do not always clearly define the management practices, and use subjective terms like “improved management”, or “best management practices” (Batjes, 2019; Paustian et al., 2016; Smith et al., 2020). Consequently, comparisons between studies might be impossible as improvement or best management practices are highly context dependent (i.e. agronomic, climatic, socioeconomic, or time context) (Rosenstock et al., 2016). Reversely, meta-analyses or original studies that evaluate the effect of specific land management practices on SOC storage provide detailed description of the land-use and management practices but their scope is generally limited to one land cover type, one broad category of land management practice, or focus on a climatic zone, a region or a country (Cardinael et al., 2018; Corbeels et al., 2019; Li et al., 2018; Poeplau and Don, 2015; Maillard and Angers, 2014).

Several standards are available for the description of land cover (e.g. FAO Land Cover Classification System, System of Environmental-Economic Accounting (SEEA)) and more recently of land-use (e.g. Intergovernmental Panel on Climate Change, SEEA) (Jansen and DiGregorio, 2002; Pesce et al., 2018). Three standards for farming practices are listed by the Agrisemantics map of data standards (Pesce et al., 2018): a list of agricultural practices established by the FAO (https://vest.agrisemantics.org/node/20351), the land-use categories in World Census of Agriculture (https://vest.agrisemantics.org/node/20353), and the SEEA Land-use Classification (https://vest.agrisemantics.org/node/20352). However, a comprehensive thesaurus and classification of management practices is lacking, especially while focussing on SOC storage. For instance, the standards for " farming practices " listed in the Agrisemantics map (https://vest.agrisemantics.org/by-theme/7705/7705/7713) are not exhaustive (e.g. empirical farmers' practices in Southern countries), nor harmonized or/and specific to SOC storage. As far as we know, there has been no attempt to deal with these shortcomings to be able to understand, quantify or extrapolate processes and drivers of SOC storage in agriculture and forestry using large databases. Therefore, the objectives of this study were: i) to compile a comprehensive thesaurus, i.e. a list of standards and specifically defined terms, for management practices driving SOC storage, ii) to keep such thesaurus easy to use for non-scientists such as soil test laboratories or land managers, and iii) to define a classification of these drivers to further enhance interoperability of databases on SOC. The aim of this paper is to present a first comprehensive thesaurus and classification of management practices in agriculture and forestry with a focus on soil organic carbon called DATA4C+.

2. Materials and Methods

2.1. Identification of SOC drivers related to land management practices

In the present work, land management practices covered croplands, grasslands and forestry practices established at the field scale, without any change in land-use. We identified land management practices which are recognized in scientific literature to influence SOC change. The literature search was conducted based on expert knowledge. A first list of meta-analyses was established by the authors, allowing the identification of relevant land management practices (e.g. Cardinael et al., 2018; Mayer et al., 2020; Smith et al., 2020, see Supplementary material 1 for some examples and Supplementary material 2 for the full list). Focus was put on meta-analyses as homogeneous definitions are a pre-requisite to conduct such analyses. Besides, the list of land management practices gathered from the meta-analyses was completed thanks to technical and institutional reports (e.g. Chotte et al., 2019; Pellerin et al., 2020; Sanz et al., 2017; Smith et al., 2007), which are hardly referenced in search engines like Scopus, Web of Science or Google Scholar. Finally, this list of practices was extensively discussed among the group of authors resulting in the selection of other practices than the initial ones. Original papers (e.g. Cardinael et al., 2018; Mayer et al., 2020; Smith et al., 2020, see Table 1 for some examples and Supplementary material for the full list), technical and institutional reports (e.g. Chotte et al., 2019; Pellerin et al., 2020; Sanz et al., 2017; Smith et al., 2007) were used to identify these land management practices.

Only land management practices explicitly described were retained. Therefore, management practices labelled as “improved” were discarded. Consequently, we included practices considered as nominal or conventional (e.g. monoculture, conventional tillage). Agroforestry was considered in this study as a land management practice, since it is defined as an agroecosystem where “forest species of trees and other wooded plants are purposely grown on the same land as agricultural crops or livestock, either concurrently or in rotation” (FAO, 2015).

2.2. Definition of drivers

Definitions of land cover classes, land-use classes, and land management practices were found in data standards (e.g. World Census of Agriculture, FAO, 2015), thesaurus (e.g. Agrovoc) and scientific literature collected at the former step of driver identification. In case a definition was lacking in the primary data source, it was collected through thematic glossaries (e.g. IPCC, 2019; “Landmark Glossary”; “WOCAT Glossary”).

2.3. Classification of land management practices

As there is currently no comprehensive thesaurus for land management practices which directly or indirectly affect SOC dynamics, we classified the single management practices gathered in the previous steps into a hierarchical tree. This hierarchical tree was built thanks to existing classifications of land management practices found in literature. These classifications usually rely on the manipulation of several components of the agroecosystem which often affect C inputs and C outputs from soils, such as the plant management, water management or soil tillage management for example (Table Supplementary material 1). We considered, in the hierarchical tree, only single land management practices. Integrated land management practices (e.g. conservation agriculture, organic agriculture) were not included as a whole, but described by their single components (e.g. conservation agriculture = no tillage, permanent soil cover, rotation/crop diversification).

Table 1. Examples of land-use change and land management practices classification for the assessment of soil organic carbon stock change (see supplementary material for the full list used)

Reference	**Forests**	**Annual and perennial croplands**	**Grasslands**	**Land-use change**
(Smith et al., 2008) IPCC report for GHG mitigation in agriculture		- Improved agronomic practices - Nutrient management - No till & residue retention - Water management - Manure application		
(Paustian et al., 2016) Land management practices for climate-smart soils		- Add nutrients; add lime; grow N fixing species - Grow cover crops; reduce or vegetate fallow fields - Reduce to economic-optimal rates - Reduce or halt tilling; implement residue retention - Improve timing and placement; use enhanced efficiency fertilizer - Rotate perennials; use agroforestry; use high-C input species; grow cover crops - Add amendments such as compost and biochar	- Convert to perennial vegetation - Restore to wetland	
(Griscom et al., 2017) Evaluation of land management practices for GHG mitigation	- Natural forest management - Improved plantations - Avoided woodfuel - Fire management	- Biochar - Trees in croplands - Nutrient management - Conservation agriculture - Improved rice	- Grazing-feed - Grazing-animal management - Optimal intensity - Legumes	- Reforestation - Avoided forest conversion - Avoided grassland conversion

(Chotte et al., 2019) Sustainable land management practices for land degradation neutrality		- Agroforestry - No/minimum tillage - Crop rotation - Intercropping - Green manuring - Composting/mulching - Manuring - Integrated crop/livestock systems - Conservation agriculture - Fertilizer use	- Reduce herd densities	- Afforestation - Reforestation

(Smith et al., 2020) Land management practices for food security, climate change mitigation, and against desertification and land degradation	Improved forest management refers to management practices in forests for the purpose of climate change mitigation. It includes a wide variety of practices affecting the growth of trees and the biomass removed, including improved regeneration (natural or artificial) and a better schedule, intensity, and execution of operations (thinning, selective logging, final cut; reduced impact logging, etc.).	- Improved cropland management is a collection of practices consisting of (a) management of the crop: including high carbon input practices, for example, improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology; (b) nutrient management: including optimized fertilizer application rate, fertilizer type (organic manures, compost, and mineral), timing, precision application, nitrification inhibitors; (c) reduced tillage intensity and residue retention; (d) improved water management: including drainage of waterlogged mineral soils and irrigation of crops in arid/ semiarid conditions; (e) improved rice management: including water management such as mid-season drainage and improved fertilization and residue management in paddy rice systems; and (f) biochar application - Practices that increase soil organic matter content include a) land-use change to an ecosystem with higher equilibrium soil carbon levels ; (b) management of the vegetation: including high carbon input practices, for example, improved varieties, rotations and cover crops, perennial cropping systems, biotechnology to increase inputs and recalcitrance of below ground carbon; (c) nutrient management and organic material input to increase carbon returns to the soil: including optimized fertilizer and organic material application rate, type, timing, and precision application; (d) reduced tillage intensity and residue retention; and (e) improved water management: including irrigation in arid/semiarid conditions	Improved grazing land management is a collection of practices consisting of (a) management of vegetation: including improved grass varieties/sward composition, deep rooting grasses, increased productivity, and nutrient management; (b) animal management: including appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification; and (c) fire management: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning (see also fire management as a separate practice below)	- Reduced grassland conversion to cropland - Reduced deforestation and degradation - Reforestation and forest restoration - Afforestation - Land-use change to an ecosystem with higher equilibrium soil carbon levels (e.g., from cropland to forest)

(Bai et al., 2019) Effect of climate-smart agriculture practices on soil carbon stocks		- Conservation tillage - no-till - reduced tillage - Cover crops - Biochar - Other agronomic practices: crop residues, nitrogen fertilization, irrigation, and crop rotation		
(Chambers et al., 2016) 4P1000 potential in the USA		- Conservation cover - Conservation crop rotation - Residue and tillage management, no-till - Strip till - Contour farming - Contour buffer strips - Residue and tillage management, reduced till - Field border - Filter strips - Grassed waterways - Strip-cropping - Vegetative barriers - Herbaceous wind barriers	- Forage and biomass planting - Prescribed grazing - Range planting	
(Corbeels et al., 2019) 4P1000 potential in sub-Saharan Africa through agroforestry and conservation agriculture		Conservation agriculture: - Minimum/no tillage - Minimum/no tillage + residues - Minimum/no tillage + residues + intercropping or rotation Agroforestry: Alley cropping Multistrata systems Fallows Parklands	Parklands	

(Pellerin et al., 2019) 4P1000 potential in mainland France		- No-tillage - Cover crops - Increase of temporary grasslands in crop rotations - Increase exogenous organic matter application - Agroforestry - Hedgerows - Cover crops in vineyards	- Moderate intensification of grasslands: fertilization, increase leguminous species, increase grass export - Haying rather than grazing	
(Conant et al., 2017) Effect of grassland management on soil carbon stocks			- Fertilization - Fire - Grazing - Grass ley - Reclamation	- Cultivation to grass - Native to grass
(Batjes, 2019) Effect of grassland management on soil carbon stocks			- Controlled grazing - Adjusting stocking rates - Improved pastures with leguminous crops - Fire management	
(Mayer et al., 2020) Effect of forest management on soil carbon stocks	- Nitrogen addition - Selection of species with N-fixing associates - Trees species selection - Management of tree species diversity - Management of stand density and thinning - Removal of forest residues - Herbivory regulation - Fire management			Afforestation

~~(Cardinael et al., 2018)~~ ~~IPCC Tier 1 coefficients for agroforestry systems~~		~~- Alley cropping~~ ~~- Fallows~~ ~~- Hedgerows~~ ~~- Multistrata systems~~ ~~- Shaded perennial crop systems~~ ~~- Silvo-arable systems~~ ~~- Parklands~~	~~- Parklands~~ ~~- Silvopastures~~ ~~- Hedgerows~~	

2.4. Design and quality control of the thesaurus

From October 2019 to October 2020, participants to the project DATA4C+ (https://www.data4c-plus-project.fr/en) carried out the editing phase of the thesaurus. Participants were junior and senior scientists from 3 French research institutions (i.e. Cirad, INRAE, IRD) that joined their expertise about organic carbon dynamics in temperate and tropical soils. A first version of the thesaurus and classification was shared and discussed among them in October 2020. The consolidation phase was carried out from November 2020 to June 2021. A second version of the thesaurus and classification was shared, discussed and validated among participants of the project in July 2021. From July 2021 to September 2021, editors of the thesaurus checked its consistency before its first available on-line version, as presented in this paper (see Fig. 1).

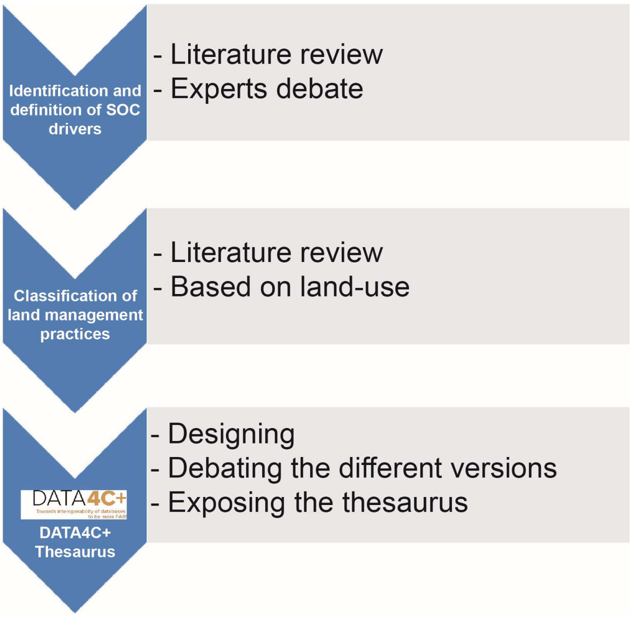

Figure 1 – Summary of the different steps to build the DATA4C+ thesaurus

3. Results

3.1. Land management practices

Land management practices were classified in three main categories according to land-use: i) land management practices in annual and perennial croplands, ii) land management practices in grasslands, and iii) land management practices in forests and tree plantations. We chose to classify the land management practices inside large categories of land-use rather than land cover for several reasons. Land-use categories are well harmonized between different standards (FAO, IPCC, SEEA, World Census of Agriculture, see Gong et al., 2009), whereas the matching of land cover categories between the main standards is less straightforward (see, for instance, Herold et al. (2009) and Yang et al. (2017) for the harmonization of FAO Land Cover Classification System with other land cover standards). Land-use categories suit well with greenhouse gas (GHG) balance accounting thanks to the IPCC framework (IPCC, 2006). Furthermore, some management practices may induce a change in land cover without changing in land-use, such as management practices regarding plant management like agroforestry practices.

In these categories, several sub-categories were created, regarding plant, biomass (through grazing and animal management in grassland, residue management in croplands, biomass fluxes in forests), and amendments management, but also erosion, water, fire, and land clearing management in the case of agroecosystems implanted after land clearing. These sub-categories are mainly inspired from Smith et al. (2020). They rely on management techniques from the point of view of the land managers, which is commonly used in literature for the classification of land management practices that affect SOC dynamics (~~Table~~ Supplementary material 1). Another classification of land management practices could be specifically based on the mechanisms affecting SOC dynamics, i.e. modification of carbon inputs and/or modification of SOM turnover. However, this approach would be less handy for a non-scientific audience. Furthermore, there are still knowledge gaps regarding the processes involved in SOC sequestration after the establishment of several management practices (Chenu et al., 2019).

3.2. The DATA4C+ thesaurus: technology, content and browsing

The DATA4C+ thesaurus is freely available at the following URL address: http://data4c-plus.net/admin/thesaurus/index.

The DATA4C+ thesaurus is connected to a PostgreSQL® database. The intuitive web interface uses the jsPlumbTree function of the jQuery library, which is a plugin that renders a reducible and extensible tree structure representing the hierarchical relationship between different nodes. In addition, the plugin uses the jsPlumb library to draw connection lines using Bézier curves between nodes. The tree is drawn dynamically from left to right and top to bottom when connecting to the database.

Each term of the database is defined by four nodes:

- data-id: term identifier. Must be unique throughout the tree
- data-parent: identifier of the parent node
- data-first-child: identifier of the first child node
- data-next-sibling: identifier of the next sibling node

The DATA4C+ thesaurus was developed by Cirad. All the source programs are available on the forge https://gitlab.com/ecosols and can be freely accessed on request under the CC BY-SA 4.0 FR license. To facilitate re-use of the DATA4C+ thesaurus, it can be downloaded as Simple Knowledge Organisation System (SKOS) format (W3C, 2009). The DATA4C+ thesaurus is accessible in Agroportal (http://agroportal.lirmm.fr/ontologies/DATA4CPLUS) to enhance its findability, accessibility, interoperability and reusability by scientists in agronomy, forestry and soil sciences. It may also be used by other end-users such as soil test laboratories to describe the soil samples analysed or by land managers to describe and report their practices (e.g. for carbon farming programmes). Additionally, the Comma Separated Values (CSV) file of DATA4C+ thesaurus is available on the data depository of Cirad (https://dataverse.cirad.fr) under the CC-BY 4.0 FR license with the DOI: https://doi.org/10.18167/DVN1/HMCPMF. The DATA4C+ thesaurus classifies ~~226~~ 224 defined terms related to land management practices in agriculture and forestry. It is organized as a hierarchical tree reflecting the drivers of SOC storage. To have access to the definition of a given term, the user must find the term in the tree and click on it. Then a “pop up” appears with the definition of the term and the source of the definition (Fig. 2). A link to the source of the definition (URL or DOI) is given for each term. By clicking on this link, a new web page appears.

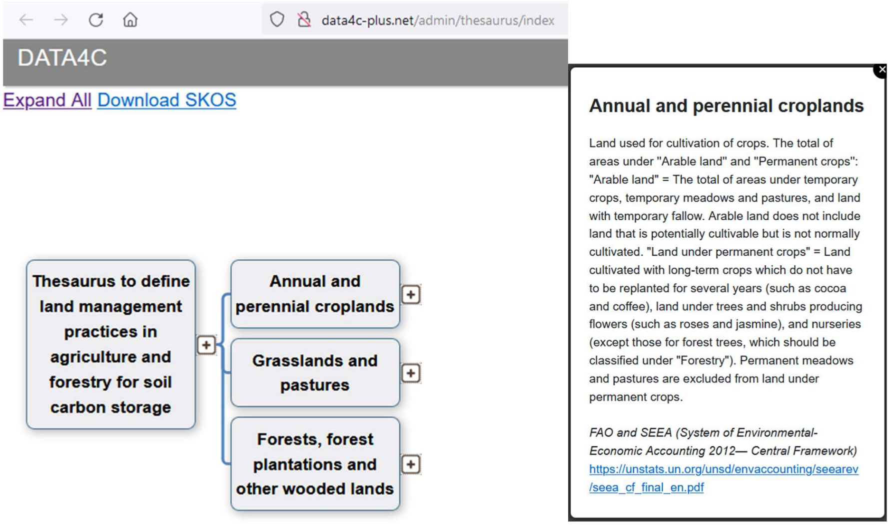

Figure 2 – Browsing hierarchical tree and definition in the DATA4C+ thesaurus (http://data4c-plus.net/admin/thesaurus/index)

4. Discussion

4.1. Less subjectivity of land-use and management practices will improve re-use of data and quality of meta-analyses

The terms “improved management practice” or “conventional agricultural” are currently used in the scientific literature despite their subjectivity (Sumberg & Giller, 2022). The use of this term implicitly means comparing one practice to another practice and describing the improved actions, which is hardly ever done. The DATA4C+ thesaurus gives a framework to describe the practices. This is vital to produce robust meta-analyses. For instance, the term “improved management of pastures” encompasses diverse agronomic practices (e.g. introduction of leguminous species, switch from mineral to organic fertilizers, no burning for land clearing, reduced grazing intensity).

The description of each of these agronomic practices is specific: species' names and plant density for the introduction of leguminous, type, amount and date of application of fertilizers for the switch from mineral to organic fertilizers, amount of biomass left on site for no burning for land clearing. Besides, their impacts on SOC stocks are highly different as highlighted by Maia et al. (2009), Conant et al. (2017), or Fujisaki et al. (2018).

4.2. More genericity in the description of management practices will improve re-use of data and quality of meta-analyses

The DATA4C+ thesaurus intends to facilitate data sharing for the evaluation of soil carbon storage through land management practices, thanks to the genericity of the proposed terms. We evaluate the DATA4C+ thesaurus against land management practices used in several meta-analyses (Table ~~2~~1). In many situations, there is an adequate matching between terms used in the meta-analyses and terms used in the thesaurus.

However, some studies use levels of details uncovered in the thesaurus, such as the species family of plants sown in the fields (Bai et al., 2019), or several tillage techniques (Jian et al., 2020), that can be grouped into larger categories used in the thesaurus (Intermediate intensity tillage or High intensity tillage~~conventional vs reduced tillage~~). These very detailed levels were not covered in the thesaurus because of the current lack of the evaluation of their effect on SOC dynamics. Indeed, the effect of soil tillage on soil carbon storage is still discussed by soil scientists (Chenu et al., 2019), and the use of numerous categories of tillage practices may weaken the significance of the observed trends. We used in the thesaurus classes of tillage intensity based on the study of Haddaway et al. (2021), which distinguished High intensity tillage from Intermediate intensity tillage depending on the inversion or not of the soil during tillage, and the performed depth of the tillage practice. This offer in our opinion transparent criteria to characterize tillage intensity.

On the other hand, several studies use broader categories than in the present thesaurus, which may prevent re-use of the dataset. This is the case for land management practices in grasslands studied by Conant et al. (2017), where categories such as "grazing" and "fire" are not further detailed, despite the wide response range of soil carbon stocks according to the intensity of grazing for instance (Abdalla et al., 2018).

Concerning meta-analyses of SOC, Beillouin et al. (2022) identified issues of low transparency, reproducibility, and updatability. Improving the quality and reliability of synthesis papers is of utmost importance as they are increasingly used to inform policy decisions with possibly large environmental and socioeconomic implications (Krupnik et al., 2019). Nosek et al. (2015) noted that advances must be made to give full and unbiased access to scientific data in line with open science practices. In that perspective, the transparency and the genericity of the terms defined in the DATA4C+ thesaurus, mostly inventoried in original papers, technical and institutional reports, will contribute to increase the quality of data and ultimately to merge and analyze data from various sources.

Table 12. Matching evaluation of land management practices assessed in meta-analyses against land management practices in the DATA4C+ thesaurus.

Source	Land management category in paper	Land management practice evaluated	Land management practice or variable in the DATA4C+ thesaurus
Bai et al. (2019)	Climate Smart Agriculture practices	No-till	No-till
		Reduced tillage	Intermediate intensity tillageReduced tillage or minimum tillage
		Cover crop	Cover crop
		Biochar	Biochar
	Crop residue	Return	Mulched residues OR Shredded residues OR Buried residues
		Remove	Exported residues
	Nitrogen fertilization	1-100	Partially covered: mineral fertilization practice is included but not the quantity supplied
		101-200	Partially covered: mineral fertilization practice is included but not the quantity supplied
		> 200	Partially covered: mineral fertilization practice is included but not the quantity supplied
	Water management	Irrigation	Irrigation
	Crop sequence	Rotational	Rotation of annual crops
		Continuous	Monoculture
	Cover crop species	*Poaceae*	Not covered in the thesaurus

		Fabaceae	Not covered in the thesaurus
		Poaceae + *Fabaceae*	Not covered in the thesaurus
Conant et al. (2017)	Grassland management	Fertilizer	Mineral fertilization
		Grazing	Several choices required in "Grazing management"
		Sowing improved grass species	Plant breeding
		Grass ley in rotation	Temporary grassland in crop rotation
		Fire	Several choices in required in "Fire management"
		Earthworms	Not covered in the thesaurus
		Irrigation	Irrigation
		Reclamation	Not covered in the thesaurus
		Silvopastoralism	Silvopastures
Shi et al. (2018)	Agroforestry practices	Alley cropping	Alley cropping
		Homegardens	Multistrata systems
		Silvopastures	Silvopastures
		Windbreaks	Hedgerows
Han et al. (2016)	Crop fertilization	Unbalanced application of chemical fertilizers	Partially covered: mineral fertilization practice is included but not the appreciation of balanced vs unbalanced application
		Balanced chemical fertilization	Partially covered: mineral fertilization practice is included but not the appreciation of balanced vs unbalanced application
		Straw retention and	Mulched residues OR Shredded residues OR Buried residues AND

		application of chemical fertilizers	Mineral fertilization
		Application of manure and chemical fertilizers	Solid manure OR liquid manure AND Mineral fertilization
Jian et al. (2020)	Tillage group	Disk tillage	Conventional tillage High or intermediate intensity tillage depending on the depth
		Sweep	Conventional tillage High or intermediate intensity tillage depending on the depth
		Tandem disk	Conventional tillage High or intermediate intensity tillage depending on the depth
		Full-tilled	Conventional tillage High intensity tillage
		Mouldboard ploughing	Conventional tillage High intensity tillage
		Harrowing	Conventional tillage Intermediate intensity tillage
		Moldboard plowing	Conventional tillage High intensity tillage
		Turnplow	Conventional tillage High intensity tillage
		Plow-till	Conventional tillage High intensity tillage
		Ridge-till	Ridge tillage High or intermediate intensity tillage depending on the tools and the depth
		Mulch tillage	Intermediate intensity tillageReduced tillage or minimum tillage
		Chisel	High or intermediate intensity tillage depending on the depthReduced tillage or minimum tillage
		Slit tillage	High or intermediate intensity tillage depending on the depthReduced tillage or minimum tillage
		Light tillage	Reduced tillage or minimum tillage Intermediate intensity tillage

		Strip-tiller tillage	Strip tillage
		Deep-till	High intensity tillage~~Conventional tillage~~
		No-tillage	No-till
Jian et al. 2020	Conservation type	Agriculture forest system	Several choices required in the category Agroforestry
		Cover crop	Cover crop
		No tillage	No-till
		Reduced tillage	~~Reduced tillage or minimum tillage~~Intermediate intensity tillage
		Organic farm	Organic agriculture
		Straw return, mulching	Mulched residues
		Stubble	Not covered in the thesaurus
		Ridging	High or intermediate intensity tillage depending on the tools and the depth~~Ridge tillage~~
		Rotation	Rotation of annual crops
		Plastic film mulching	Not covered in the thesaurus
		Interplanting	Intercropping
		Combination of two	Not covered in the thesaurus
		Organic farm with cover crop as green manure	Organic agriculture AND Cover crop
		Organic farm with no tillage	Organic agriculture AND No-till

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4.3. Future development of the DATA4C+ thesaurus: uses and accrual

The DATA4C+ thesaurus is expected to be used by scientists in agronomy, forestry and soil sciences with the aim of uniformizing the description of practices influencing SOC in their original research. As it was developed to be simple and easy-to-use, the thesaurus may also be used by several end-users as land managers (e.g. to report their practices for carbon farming) or by laboratories to describe the soil samples analysed (e.g. metadata on the sample). The generated data will therefore be more easily to retrieve and to be integrated to perform meta-analyses in particular. Another perspective will be to mobilize the DATA4C+ thesaurus to feed models on SOC dynamics with more site-specific data. However, such perspective would need to enrich the DATA4C+ thesaurus with vocabulary related to annual carbon inputs to enhance carbon inputs to soil (e.g. Bolinder et al., 2007). Accrual of the DATA4C+ thesaurus could also be focused on emerging practices and empirical farmers' practices, which are poorly studied by researchers. Promotion and ~~P~~peer-reviewing of the updated versions of the DATA4C+ thesaurus will be performed by the Scientific and Technical Committee of the 4 per 1000 Initiative (https://4p1000.org/). Versioning of the DATA4C+ thesaurus will be done at the following URL address: http://data4c-plus.net/admin/thesaurus/index, in Agroportal (http://agroportal.lirmm.fr/ontologies/DATA4CPLUS) and on the data repository of Cirad (https://doi.org/10.18167/DVN1/HMCPMF). Suggestions of accrual could be sent to the corresponding author or at the following email address: data4c@cirad.fr .

5. Conclusion

The DATA4C+ thesaurus is the first attempt to compile and classify the land-use and management practices in agriculture and forestry influencing SOC storage. Future uses of the DATA4C+ thesaurus will be crucial to improve and enrich it, but also to raise the quality of meta-analyses on SOC, and ultimately help policy-makers to identify efficient agricultural and forest management practices to improve SOC storage. In that sense, the DATA4C+ thesaurus is a contribution to SDG 17 “Partnerships for the goals” (i.e. goals 17.6 and 17.7).

Appendix

Supplementary material: the full list of references, technical and institutional reports used to identify the land management practices.

Code availability

The DATA4C+ thesaurus was developed by Cirad and Khaméos. All the source programs are available on the forge https://gitlab.com/ecosols and can be freely accessed on request under the CC BY-SA 4.0 FR license.

Data availability

The DATA4C+ thesaurus is accessible in Agroportal (http://agroportal.lirmm.fr/ontologies/DATA4CPLUS). The CSV file of DATA4C+ thesaurus is available on the repository of Cirad in the Dataverse CIRAD (https://dataverse.cirad.fr) under the CC-BY 4.0 FR license with the DOI: https://doi.org/10.18167/DVN1/HMCPMF.

Author contributions

Kenji Fujisaki led the inventory and analyses of resources to build the thesaurus. François Thévenin (Khaméos) and Jean-Baptiste Laurent did the informatic development of the thesaurus. Antonio Bispo, Tiphaine Chevallier and Julien Demenois supervised the conceptualization of the thesaurus. Kenji Fujisaki and Julien Demenois prepared the manuscript with contributions from all the co-authors. All the co-authors reviewed the thesaurus and the manuscript.

Competing interest

The authors declare that they have no conflict of interest.

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